ELECTRONIC SUPPLEMENTARY INFORMATION

Deciphering the Roles of Multiple Additives in Organocatalyzed Michael Additions**

Z. Inci Günler, Dr. I. Alfonso, Dr. C. Jimeno.*Institute of Advanced Chemistry of Catalonia (IQAC-CSIC).E-mail: ciril.jimeno@iqac.csic.es

Dr. X. Companyó, Dr. J. Burés.*Imperial College of London.E-mail: j.bures@imperial.ac.uk

Prof.Dr. M. A. Pericàs.*Institute of Chemical Research of Catalonia (ICIQ).E-mail: mapericas@iciq.es

Table of Contents

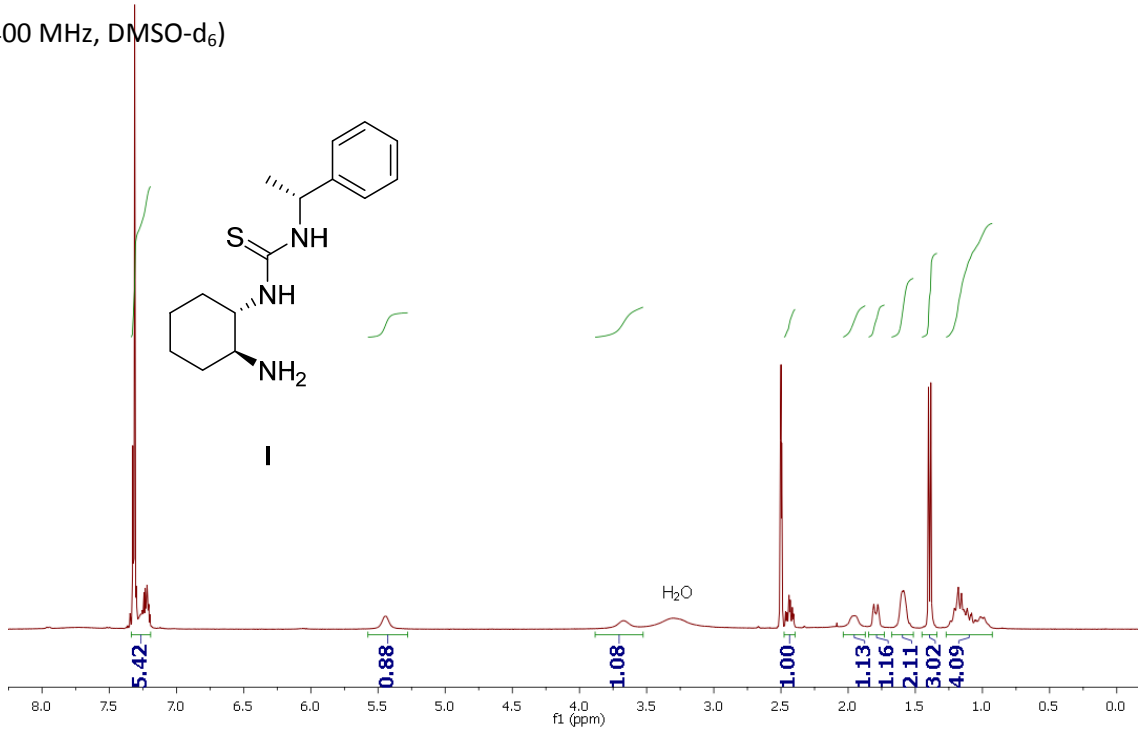
1. General

All the reagents were purchased from Aldrich or TCI and used without any further purification. The solvents were directly used from bottle unless otherwise is indicated. Anhydrous solvents were obtained from a Solvent Purification System. TLC chromatography was performed on silica gel 60 F_{254} aluminum sheets. Flash chromatography was performed using silica gel P60 (200-500 mesh). HPLC analyses were performed using a Shimadzu Prominence modular equipment with autosampler and UV-Vis detector. The characterization of products by NMR was performed on an automated Varian VNMRS 400 MHz equipped with a One NMR Probe. ^{1}H NMR kinetic experiments were recorded on Bruker DRX-400 MHz equipped with a BBFO 5 mm Prove or Bruker 500 MHz equipped with a cryoprobe.

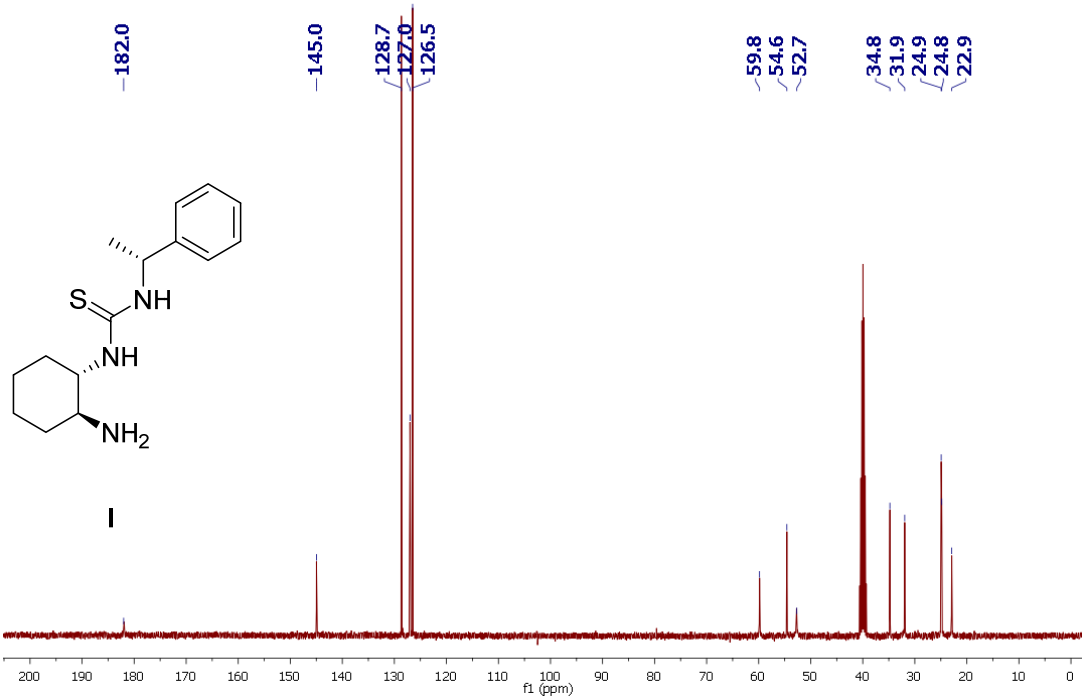
2. Preparation and NMR spectra of catalyst I

Catalyst **I** was prepared according to a described procedure and matches literature data.[1] Unprotected (*1S,2S*)-diaminocyclohexane was used instead of the mono Boc-protected diamine to avoid potential acid contamination during the deprotection step.

(400 MHz, DMSO-d_6)

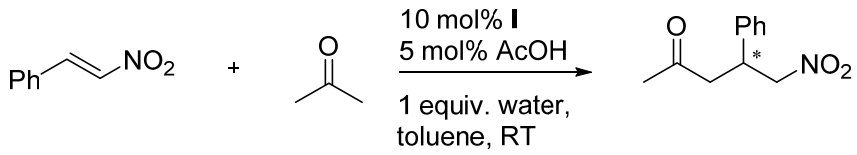


(100 MHz, DMSO-d_6)



[1]S. B. Tsogoeva, S. W. Wei;*Chem. Commun.*,**2006**, 1451-1453.

3. EnantioselectiveMichael addition of acetone to nitrostyrene

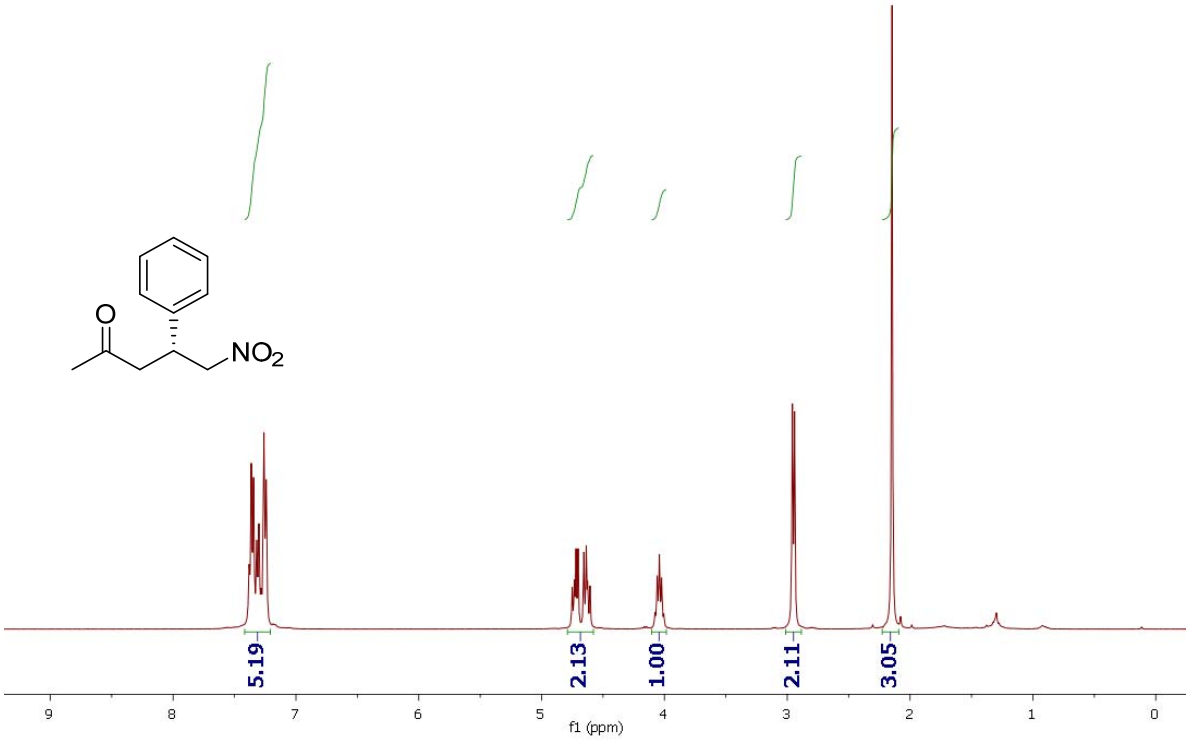


$[1]_0$ = 0.15 M **2** **3a**

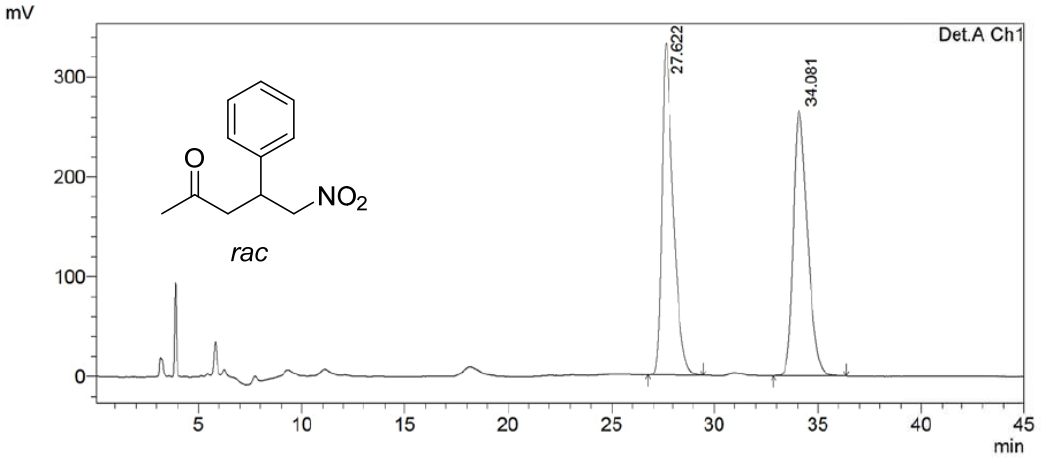
In a vial, catalyst **I** (0.1 equiv., 0.0335 mmol, 9.3 mg) and nitrostyrene **1** (1 equiv., 0.335 mmol, 50 mg) were weighed and dissolved in 1.9 mL of toluene. To this clear solution, 0.05 equiv. of AcOH was added (using 100 µL of a stock solution of 0.168 mmol, 10 µL AcOH in 1 mL toluene). Finally, 1 equiv. of water and 10 equiv. of acetone were added (using 0.25 mL of a stock solution of 0.335 mmol, 24 µL water in 1 mL acetone). The reaction was stirred at room temperature for 24 hours. To quench the reaction, water was added to the reaction vial and the organic phase was extracted with EtOAc(x3). The combined organic layers were dried over anhydrous $MgSO_4$. The solvent was evaporated and the crude mixture was directly analyzed by ^{1}H NMR to determine the conversion. Purification by flash chromatography (EtOAc:Hexane= 1:4) afforded the product **3a**. Enantiomeric excess was determined by HPLC by comparison with the authentic racemic compounds (Phenomenex Lux 5u-Amylose-2 column,Hexane:*i*PrOH= 90:10, 1 mL/min, 209 nm). HPLC samples were directly prepared from the crude reaction mixture.

3.1. ^{1}H NMR spectrum of Michael adduct 3a

(400 MHz, $CDCl_3$)

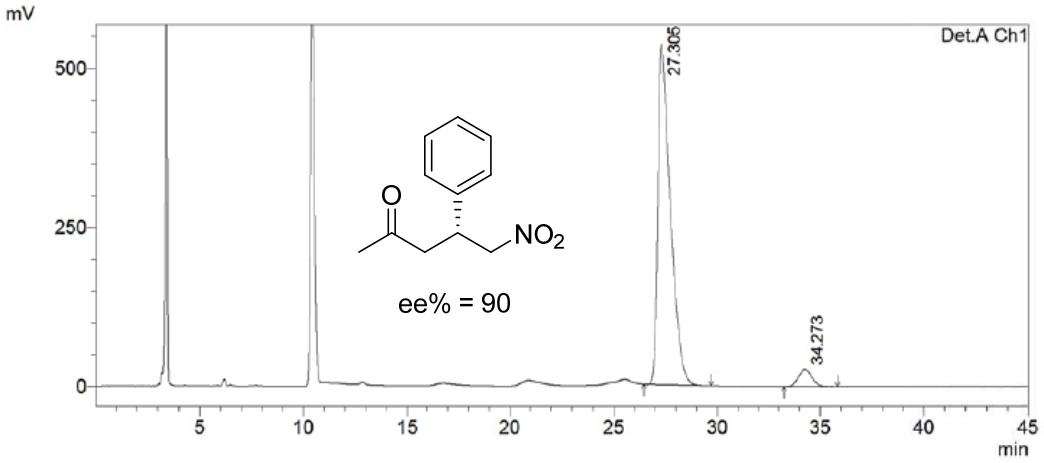


3.2. HPLC chromatograms of Michael adduct 3a



Detector A Ch1 209nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	27.622	13392042	332685	51.396	55.601
2	34.081	12664406	265661	48.604	44.399
Total		26056448	598346	100.000	100.000



Detector A Ch1 209nm

Peak#	Ret. Time	Area	Height	Area %	Height %
1	27.305	22544256	535394	94.879	95.185
2	34.273	1216824	27084	5.121	4.815
Total		23761079	562479	100.000	100.000

The *ee* value was measured along the reaction. It stays constant over time.

time (h)	ee%
1.3	90
3	90
5	90
24	90

4. Quantitative ^{1}H NMR kinetic analysis

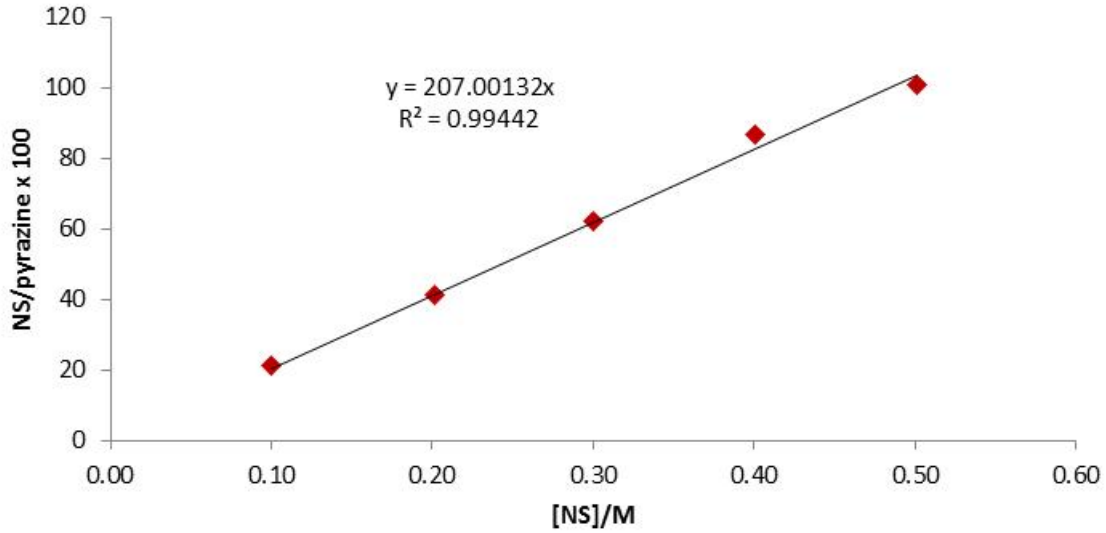
4.1. Materials and general procedure for NMR kinetic experiments

D_8-toluene (D % 99.6 ampoules of 1 mL) was purchased from Sigma-Aldrich. NMR spectra were recorded on Bruker DRX-400 MHz equipped with a BBFO 5 mm Prove. A capillary with pyrazine (δ= 7.90 ppm) was used as an external standard to quantify the concentration of the different species. To achieve quantitative data for all the species we measured the 90 degree flip angle (P1/4) and the longitudinal relaxation time (T1) for pyrazine as 7.5 s (all the species had a relaxation time lower than pyrazine). Relaxation delay (D1) was calculated as 37.5 s (7.5 s x 5) and used in all kinetic experimeriments.

4.2. Calibration curve for qNMR

To calibrate the pyrazine capillary five different solutions of known concentration of nitrostyrene **1** (NS) were prepared.^{1}H NMR of each solution with the capillary of pyrazine was recorded with ns= 8.The signals of pyrazine and NS (δ= d, 7.74 ppm) were integrated and the ratios of areas were plotted vs. the concentration of nitrostyrene.

Concentration of NS [M]	(AreaNS/Area pyrazine)×100
0.0998	21.18
0.2018	41.47
0.3004	62.40
0.4003	86.54
0.5008	100.62

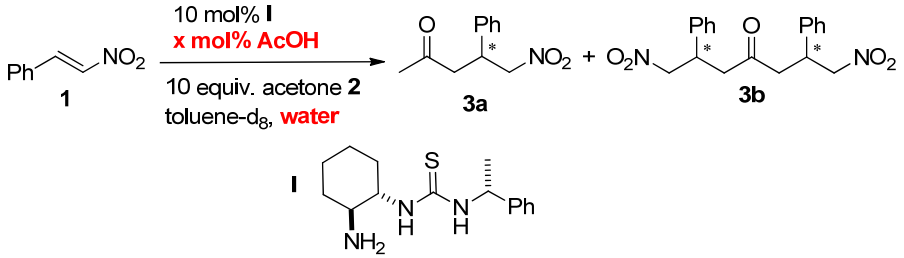


4.3. General procedure for kinetic experiments

7.5 mg (0.027 mmol) of catalyst **I** was weighed directly into NMR tube. The other reagents were added from common stock solutions in the indicated order below in function of experiment required. The reaction starting time was recorded just after the addition of the nitrostyrene (last reagent added). The shimming was done as fast as possible using the same reaction tube once the reaction was setted up (4 min approximately).

- **Stock solution A (nitrostyrene):** 201.4 mg (1.35 mmol) nitrostyrene in 1 mL d_8-toluene
- **Stock solution B (AcOH):**
  - **for 10 mol% AcOH:** 162.4 mg (155.5 µL, 2.7mmol) of acetic acid in 1 mLd_8-toluene. 0.1 mL of this solution was diluted to 1 mL d_8-toluene.
    Final solution: 0.27 mmol AcOH / mL solution
  - **for 5 mol% AcOH:** 81.2 mg (77.4 µL, 1.35mmol) of acetic acid in 1 mL d_8-toluene. 0.1 mL of this solution was diluted to 1 mLd_8-toluene.
    Final solution: 0.135 mmol AcOH / mL solution
  - **for 2.5mol% AcOH:** 40.5 mg (38.7 µL, 0.675 mmol) of acetic acid in 1 mL d_8-toluene. 0.1 mL of this solution was diluted to 1 mL d_8-toluene.
    Final solution: 0.0675 mmol AcOH / mL solution
- **Stock solution C (H_2O):**
  - **for 1 equiv. H_2O:** 24.3 µL H_2O (1.35 mmol) in 1 mL acetone.
  - **for 0.5 equiv. H_2O:** 24.3 µL H_2O (1.35 mmol) in 2 mL acetone.

Reagent addition order for the different experiments



i. ''no extra water added'' reactions (conditions B):

+ 100 µL toluene- d_8
+ 200 µL acetone
+ 100 µL stock soln. B
+ 200 µL stock soln. A

ii. ''added water'' reactions (conditions C):

+ 100 µL toluene- d_8
+ 200 µL stock soln. C
+ 100 µL stock soln. B
+ 200 µL stock soln. A

4.4. Concentration *vs* time plots at different AcOH and water amounts

The same colors and different symbols are used for the same acid and different water amount sets.

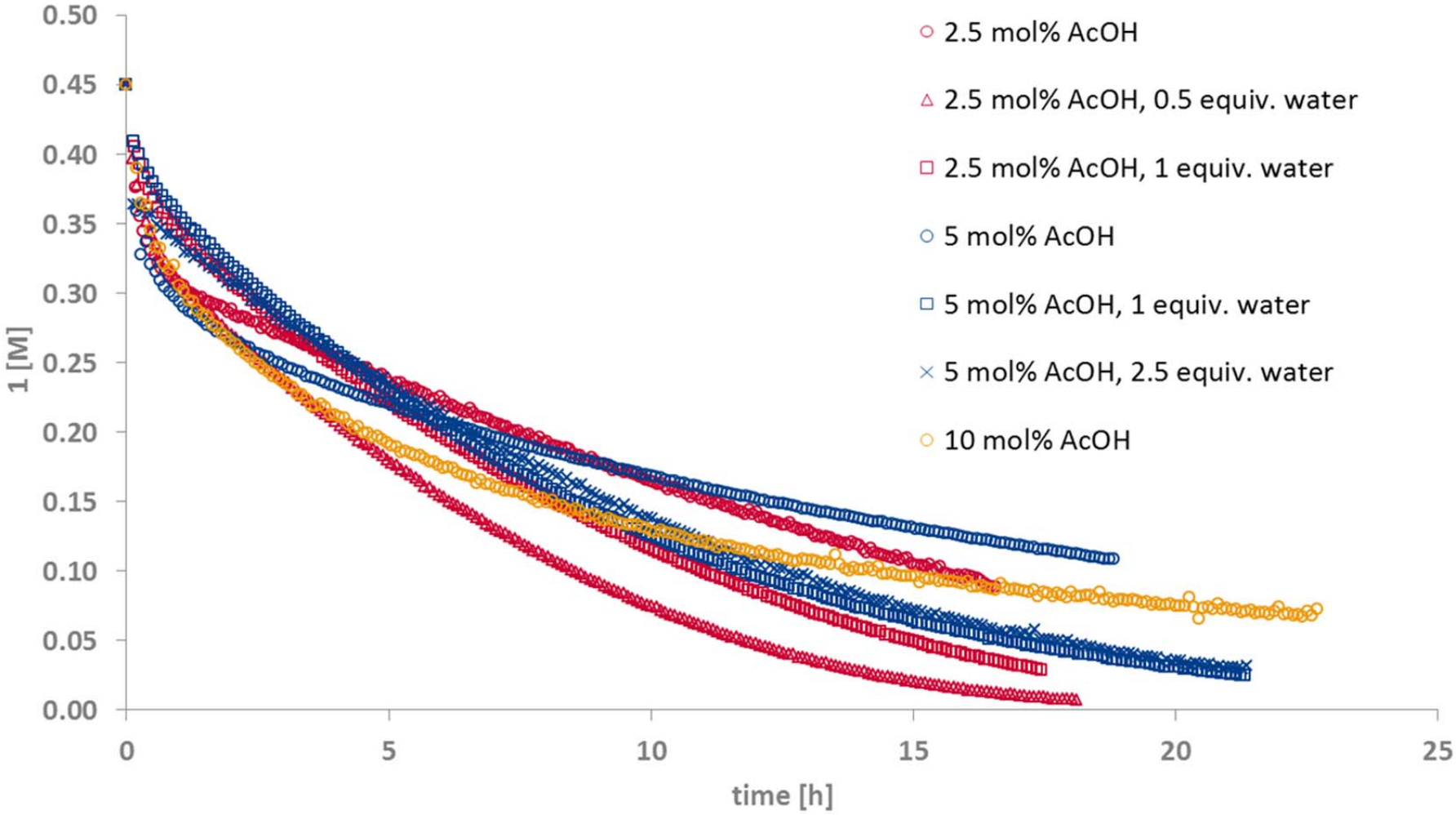


Figure 1. Consumption of nitrostyrene **1** over time under different conditions

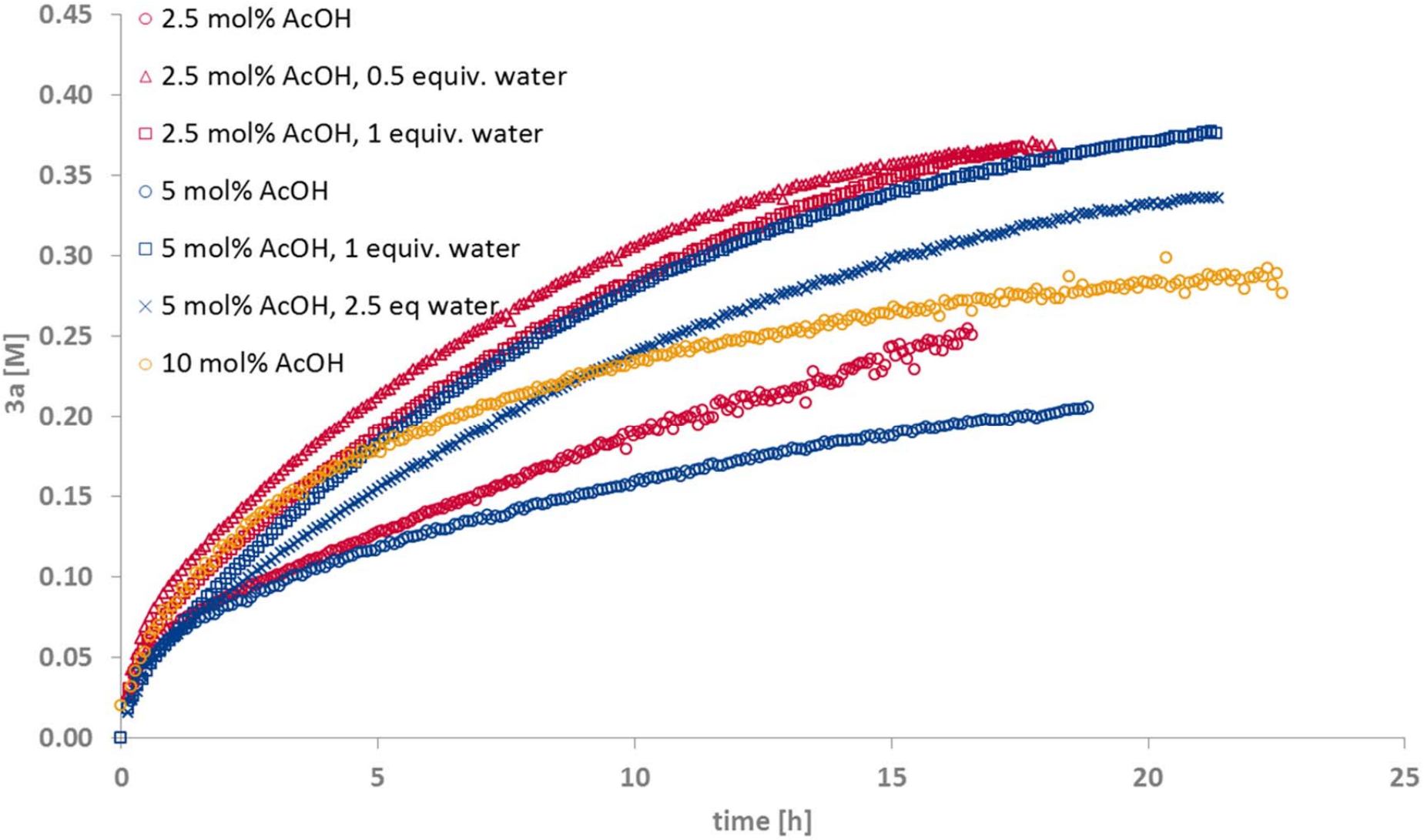


Figure 2. Formation of addition product **3a** over time under different conditions

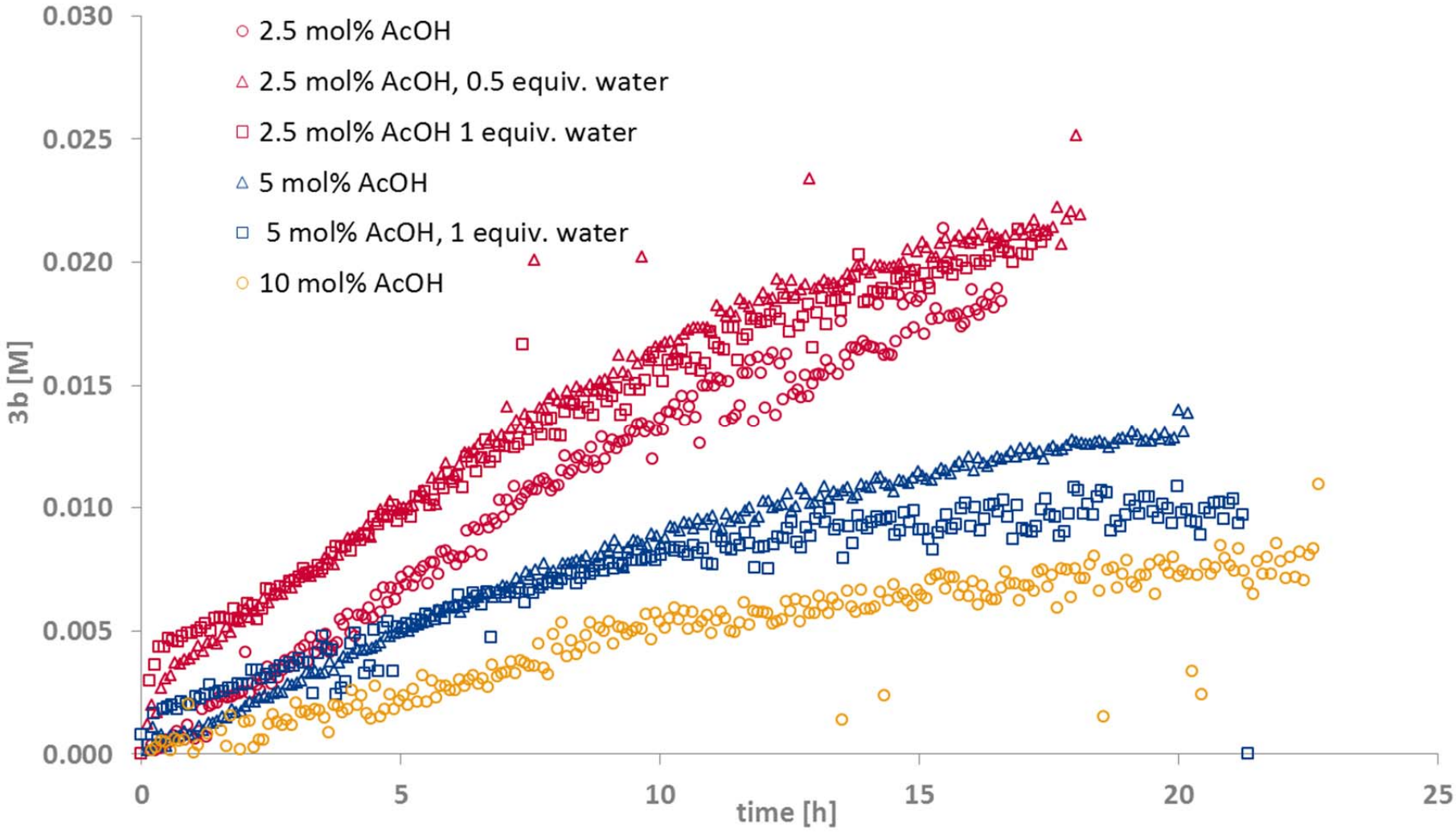


Figure 3. Formation of double addition side product **3b** over time under different conditions

4.5 Catalytic species profile over the reaction course (Conditions A):

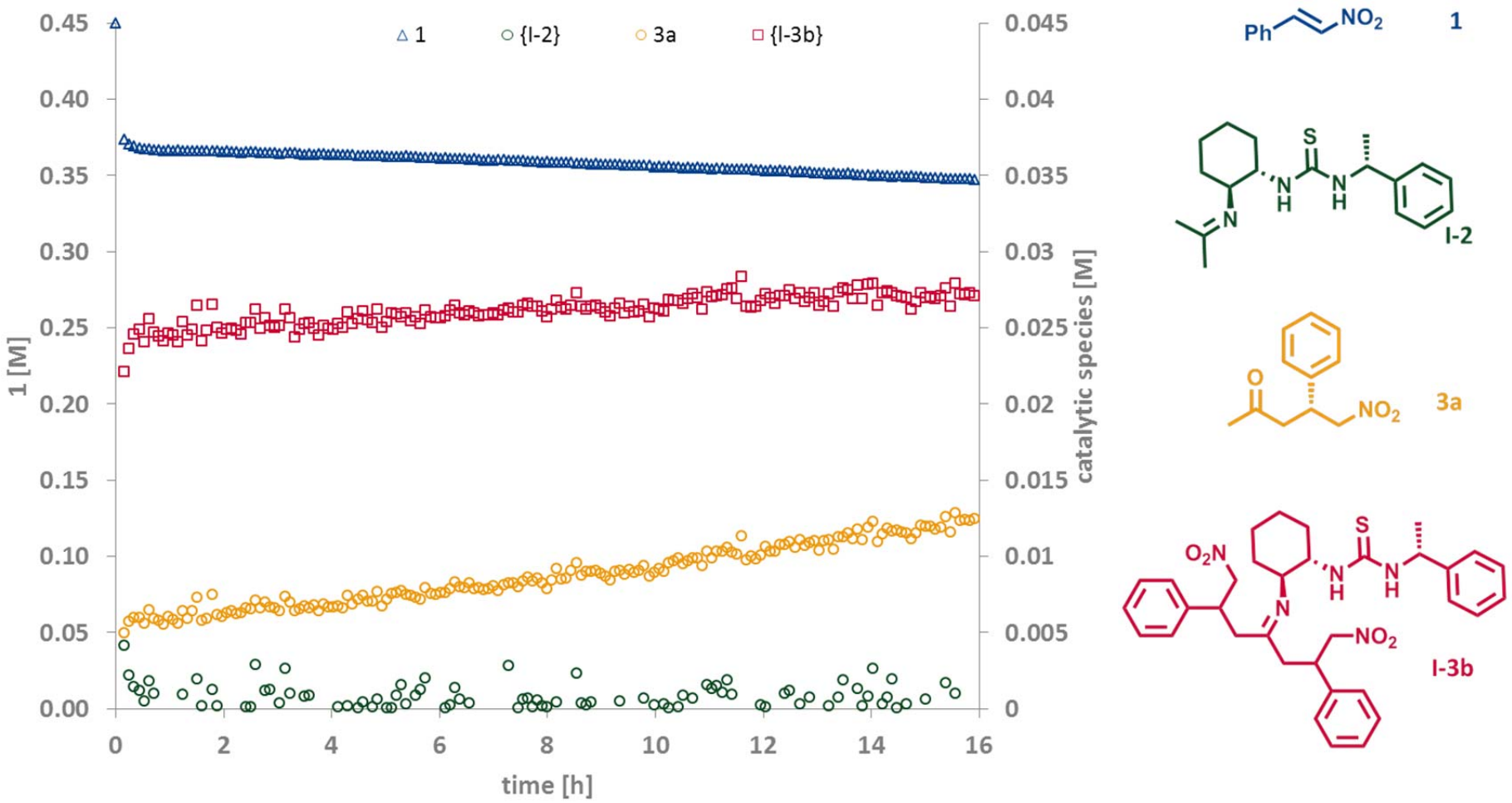
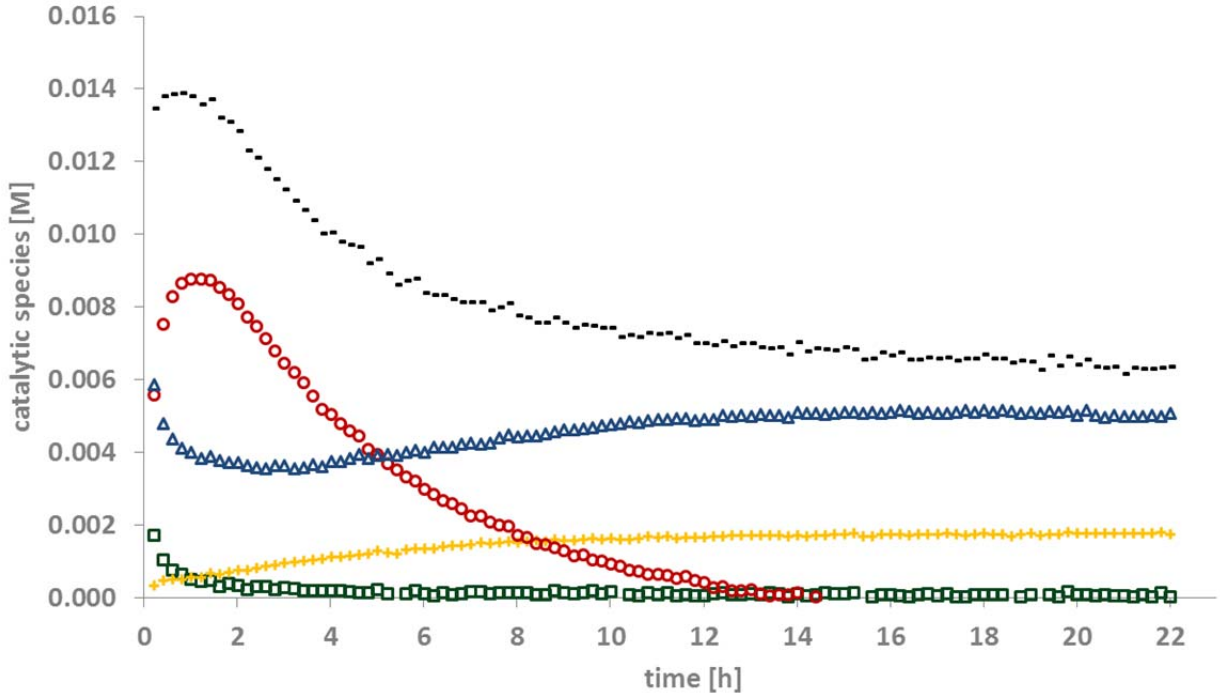


Figure 4. Reaction profile under ''no extra water added, no AcOH'' conditions (Conditions A), $[\mathbf{1}]_0$=0.45 M, 10 equiv. acetone, 10 mol% **I**. Nitrostyrene concentration is shown in the left Y axis. Catalytic species and the addition product **3a** concentrations are shown in the right Y axis. Recorded on a Bruker Avance 600 MHz equipment.

4.6 Catalytic species profile over the reaction course (Conditions B):



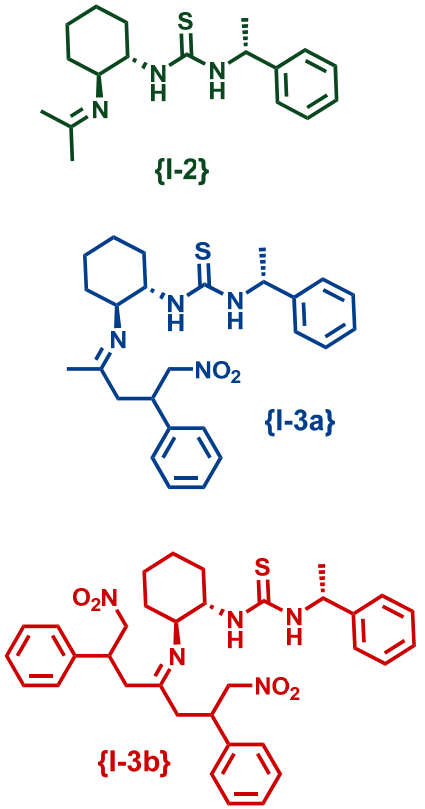
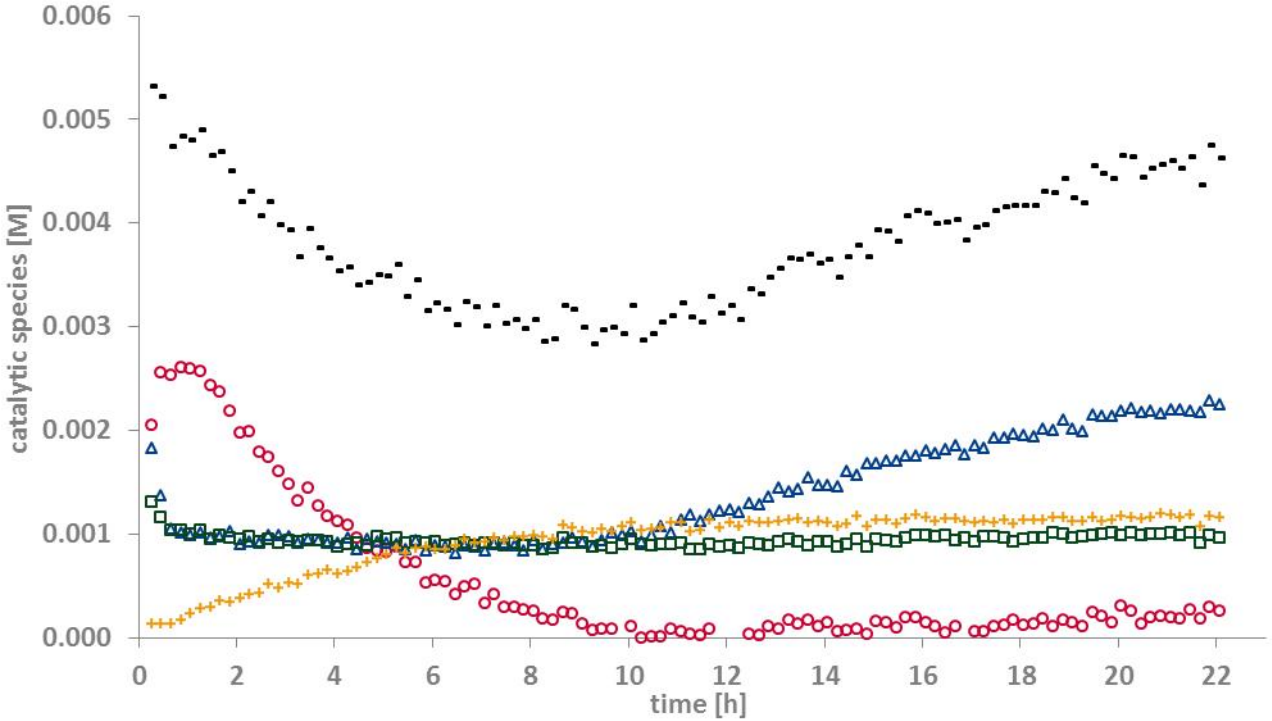
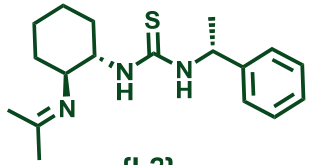


Figure 5. Catalytic species profile determined by ^{1}H NMR during the reaction under ''no extra water added' conditions (Conditions B). [**1**]$_0$=0.45 M, 5 equiv. acetone, 10 mol% **I**, 5 mol% AcOH. **{I-2}**, green; **{I-3a}**, blue; **{I-3b}**, red; unknown species, yellow; total concentration of *detected* catalytic species, black hyphen. Recorded on a Bruker 500 MHz spectrometer equipped with a cryoprobe.

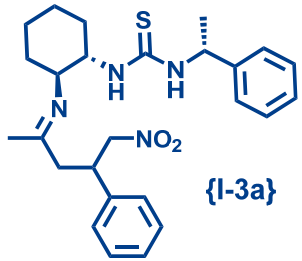
The concentration of catalyst-acetone imine {**I-2**} decreases fast from the beginning of the reaction and then stays at a very low level (green squares). Catalyst-product imine {**I-3a**} concentration (blue triangles) also decreases at the beginning but after the reaction is *ca*. 50% conversion its concentration increases again slowly and remains constant thereafter. In contrast, concentration of the catalyst-double addition product imine {**I-3b**} increases along the reaction up to a maximum at *ca*. 0.009 M, and then decreases down to very low concentrations at the end of the reaction (red circles). This behavior suggests an equilibrium between **{I-3a}** and **{I-3b}**. ^{1}H NMR signals corresponding to unknown species that we attribute to catalyst decomposition products (yellow crosses) are initially at very low intensity, but the concentration of these species increases constantly with time. The total concentration of *detected* catalytic species decreases constantly along the reaction, from 0.014 M to 0.006 M (black hyphens).

4.7 Catalytic species profile over the reaction course (Conditions C):

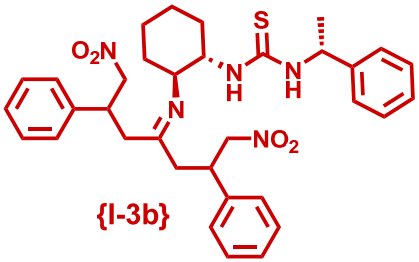




{I-2}



{I-3a}

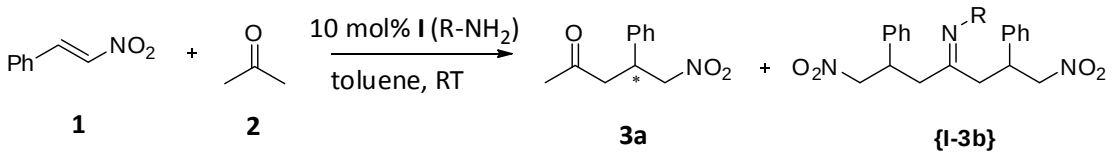


{I-3b}

Figure 6. Catalytic species profile determined by ^{1}H NMR during the reaction under acid and water added (Conditions C).[**1**]$_0$=0.45 M, 5 equiv. acetone, 10 mol% **I**, 5 mol% AcOH, 1 equiv. water. **{I-2}**, green; **{I-3a}**, blue; **{I-3b}**, red; unknown species, yellow; total concentration of *detected* catalytic species, black hyphen. Recorded on a Bruker 500 MHz spectrometer equipped with a cryoprobe.

The concentration of catalyst-acetone imine {**I-2**} decreases fast from the beginning of the reaction and then stays at a very low but appreciable level (*ca*. 0.001 M, green squares). Catalyst-product imine {**I-3a**} concentration (blue triangles) decreases fast at the beginning but afterwards stabilizes at ca. 0.001 M, and after 10 hours its concentration increases again slowly. In contrast, concentration of the catalyst-double addition product imine {**I-3b**} increases fast at the beginning up to a maximum at *ca*. 0.003 M, and then decreases down slowly to very low concentrations at the end of the reaction (red circles). This behavior suggests an equilibrium between **{I-3a}** and **{I-3b}**. ^{1}H NMR signals corresponding to unknown species that we attribute to catalyst decomposition products (yellow crosses) are initially at very low intensity, but the concentration of these species increases up to 0.001 M and stays constant after 6 hours. The total concentration of *detected* catalytic species decreases constantly along the reaction, from 0.005 M to 0.003 M, at around 8-10 hours. Afterwards the total concentration increases slowly to the original level (black hyphens).

4.8. Characterization of intermediate species



In the absence of added water and AcOH (Conditions A, $[\mathbf{1}]_0$=0.45 M, 10 equiv. acetone, 10 mol% **I**), the catalyst-double addition imine intermediate **{I-3b}** and the product **3a** formed cleanly and could be fully characterized by NMR.

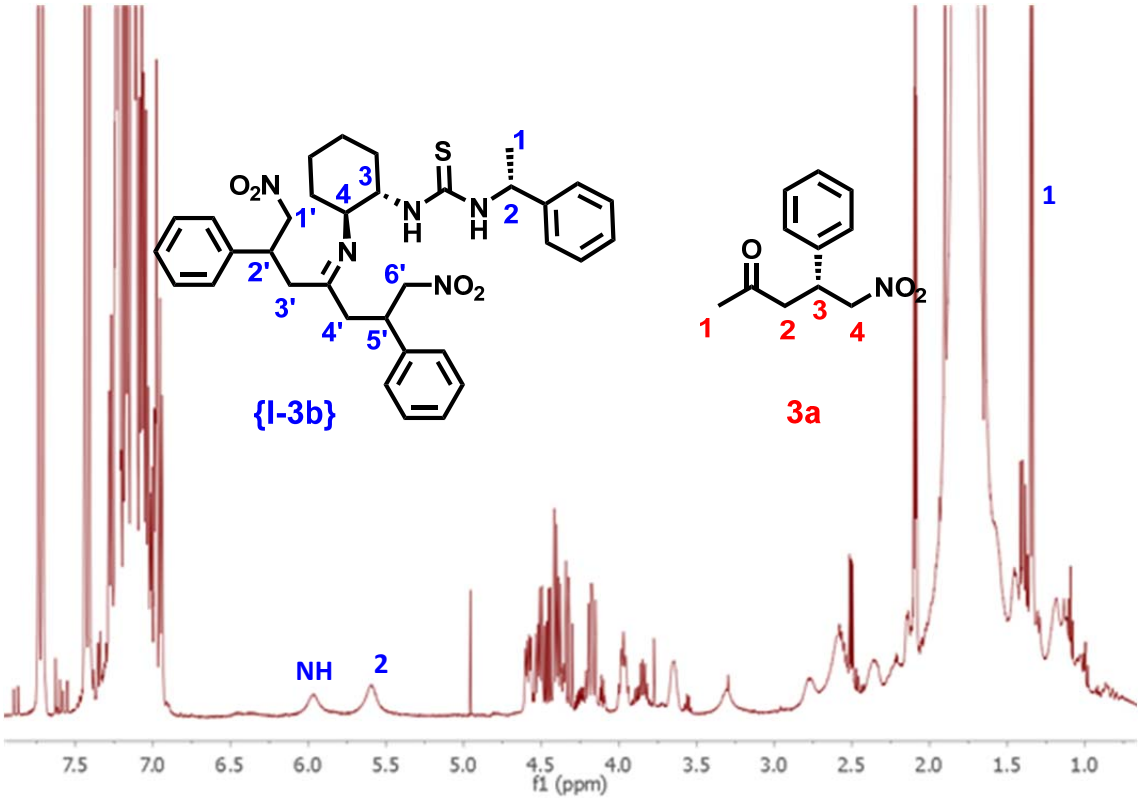


Figure 7. ^{1}H NMR characterization of the catalytic species **{I-3b}** and product **3a**. Performed in the absence of added water and AcOH (Conditions A).

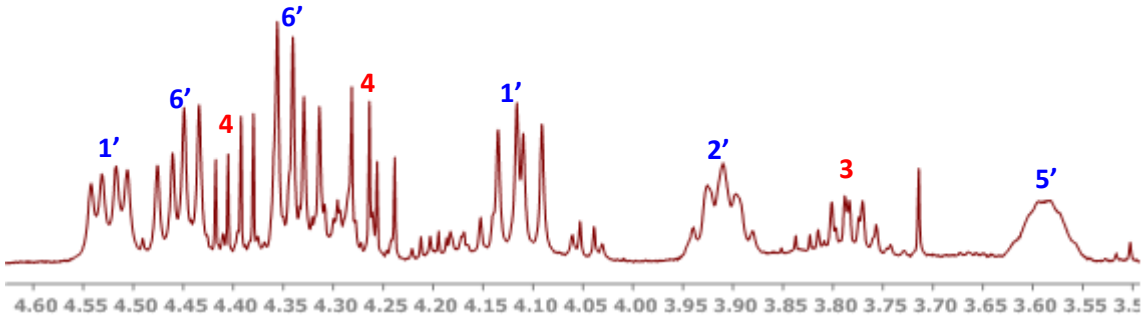


Figure 8. Expansion of ^{1}H NMR spectrum range 3.50-4.75 ppm

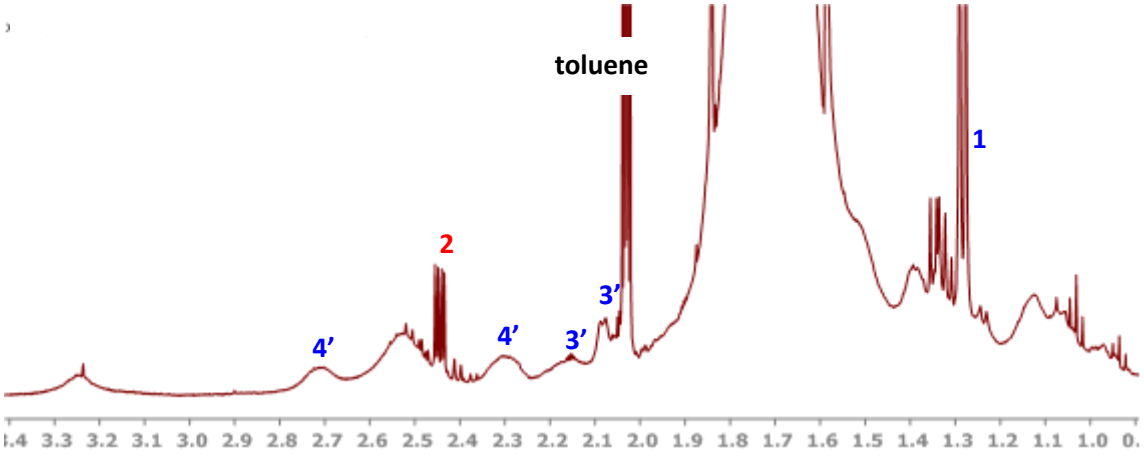


Figure 9. Expansion of ^{1}H NMR spectrum range 1.0-3.4 ppm

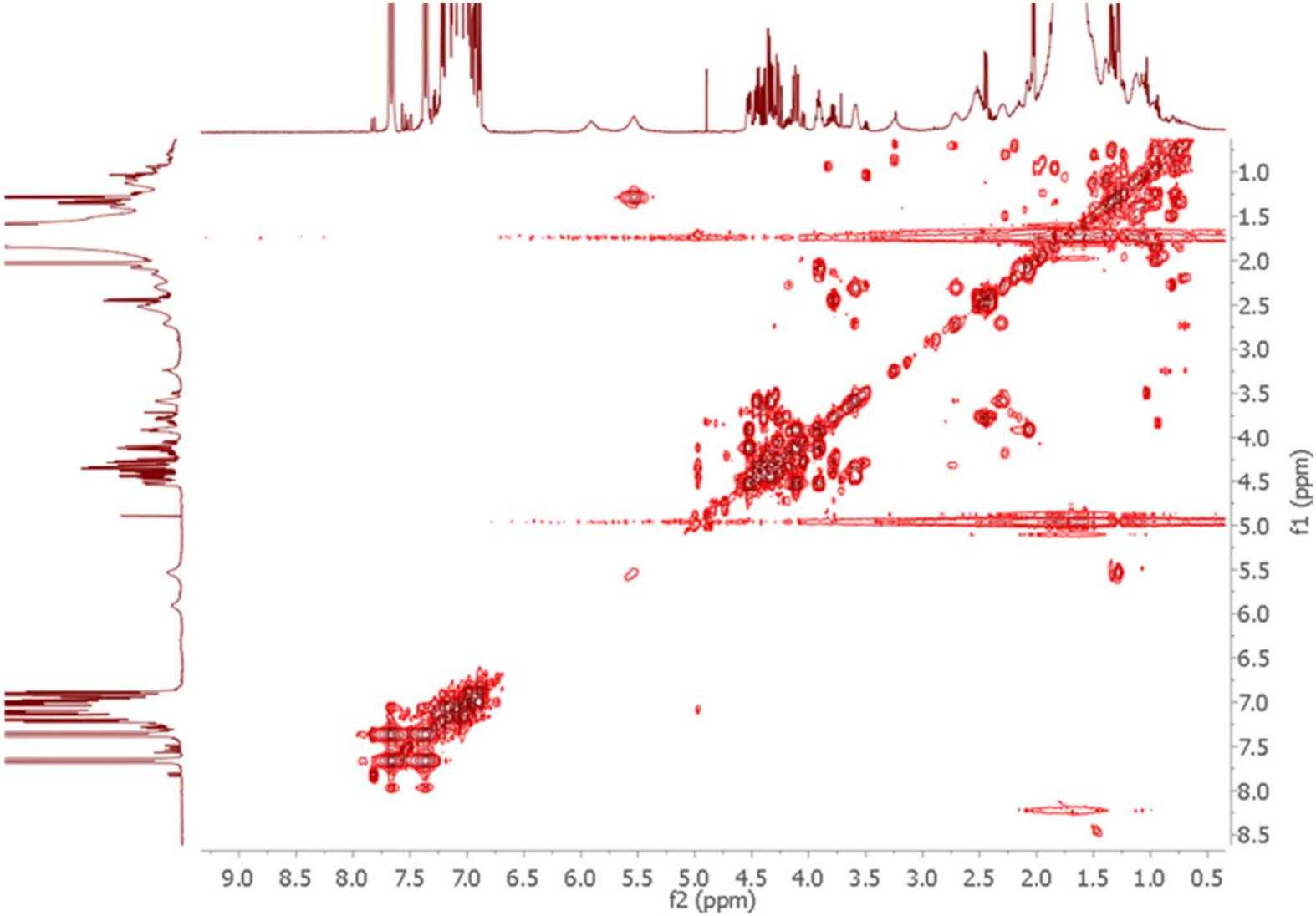


Figure 10. Full COSY NMR Spectrum in the absence of added water and AcOH (Conditions A).

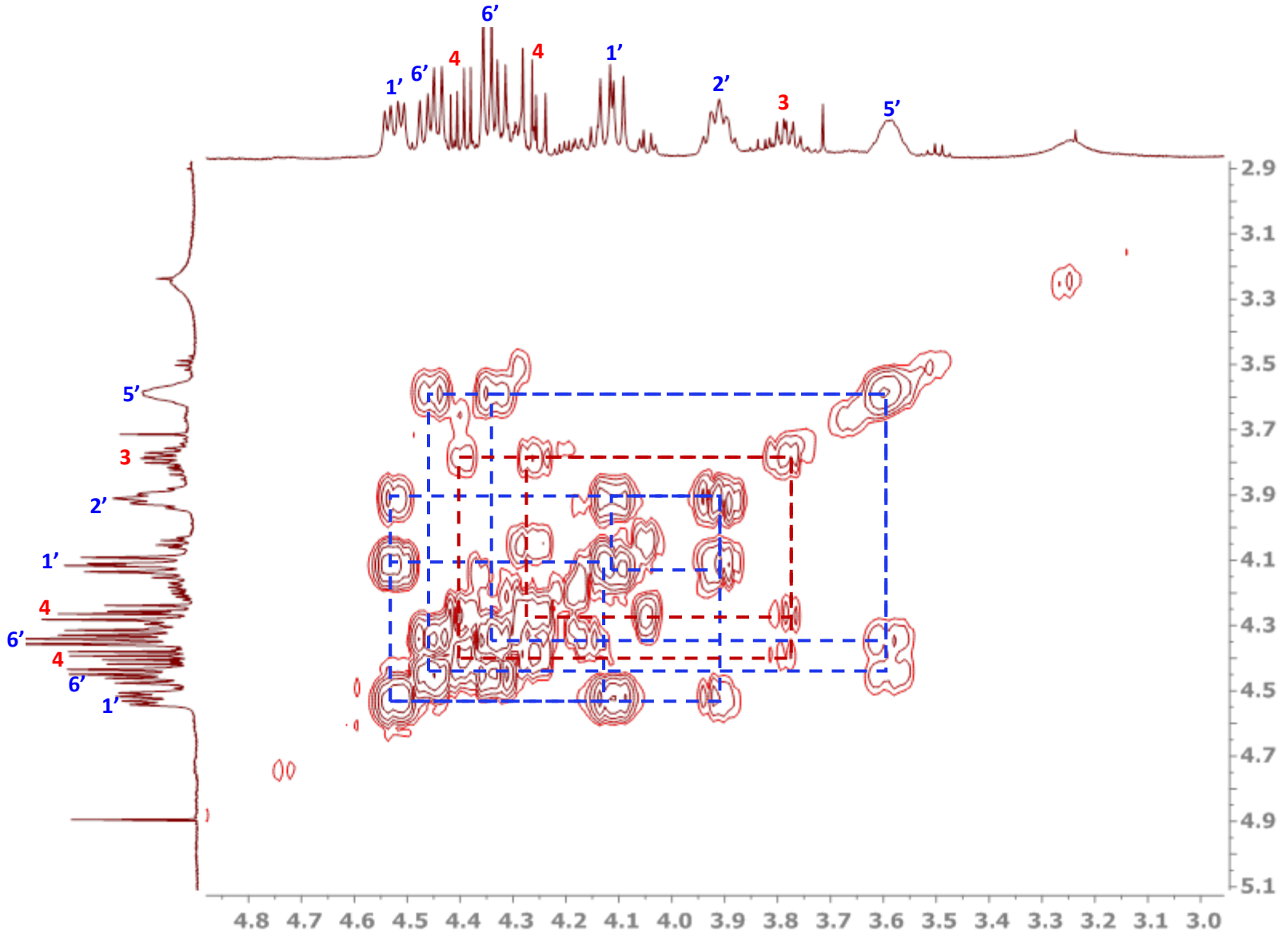


Figure 11. COSY cross peaks on the range 1.5-4.5 ppm

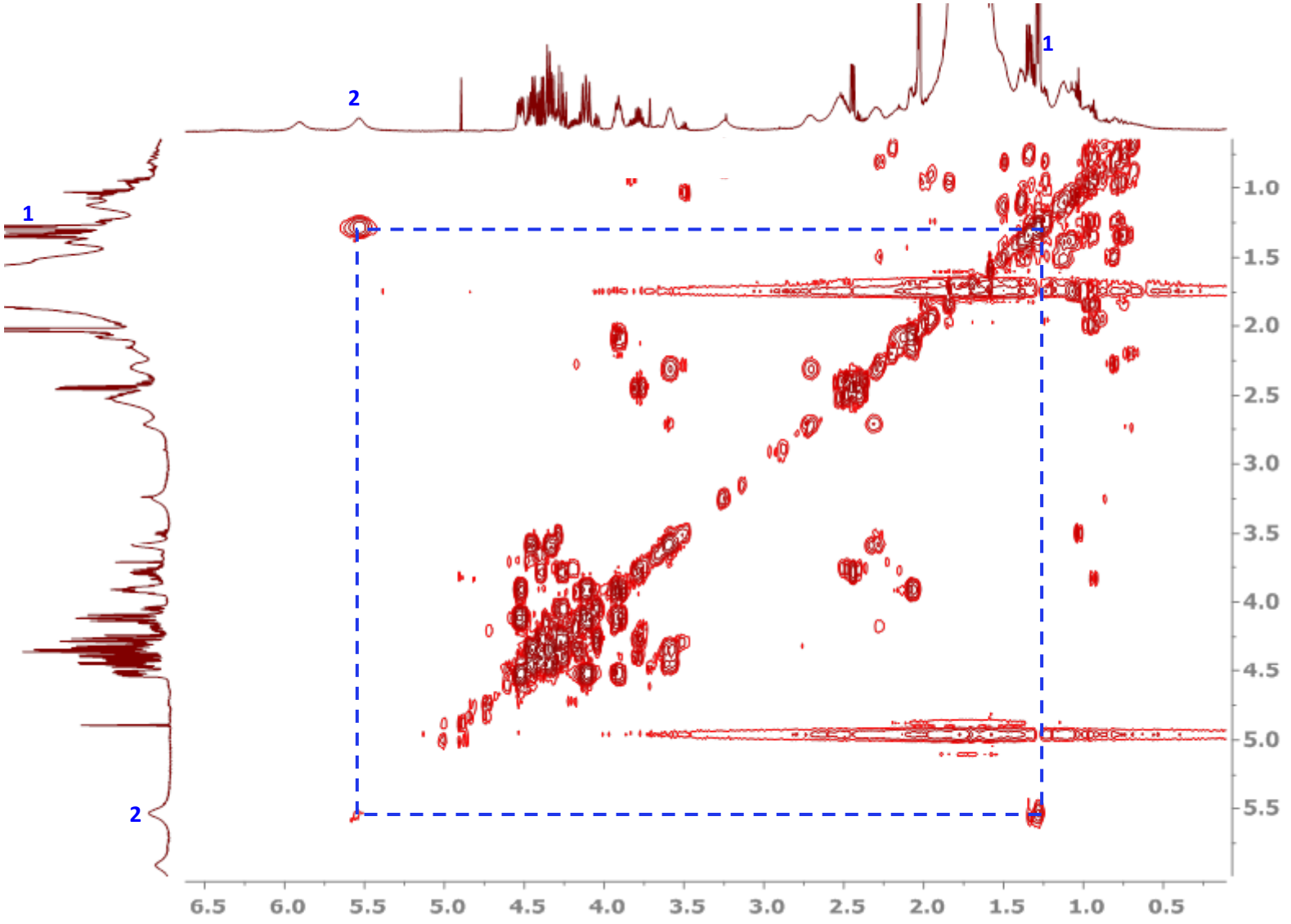


Figure 12. COSY cross peak between protons 1 and 2 of compound **{I-3b}**

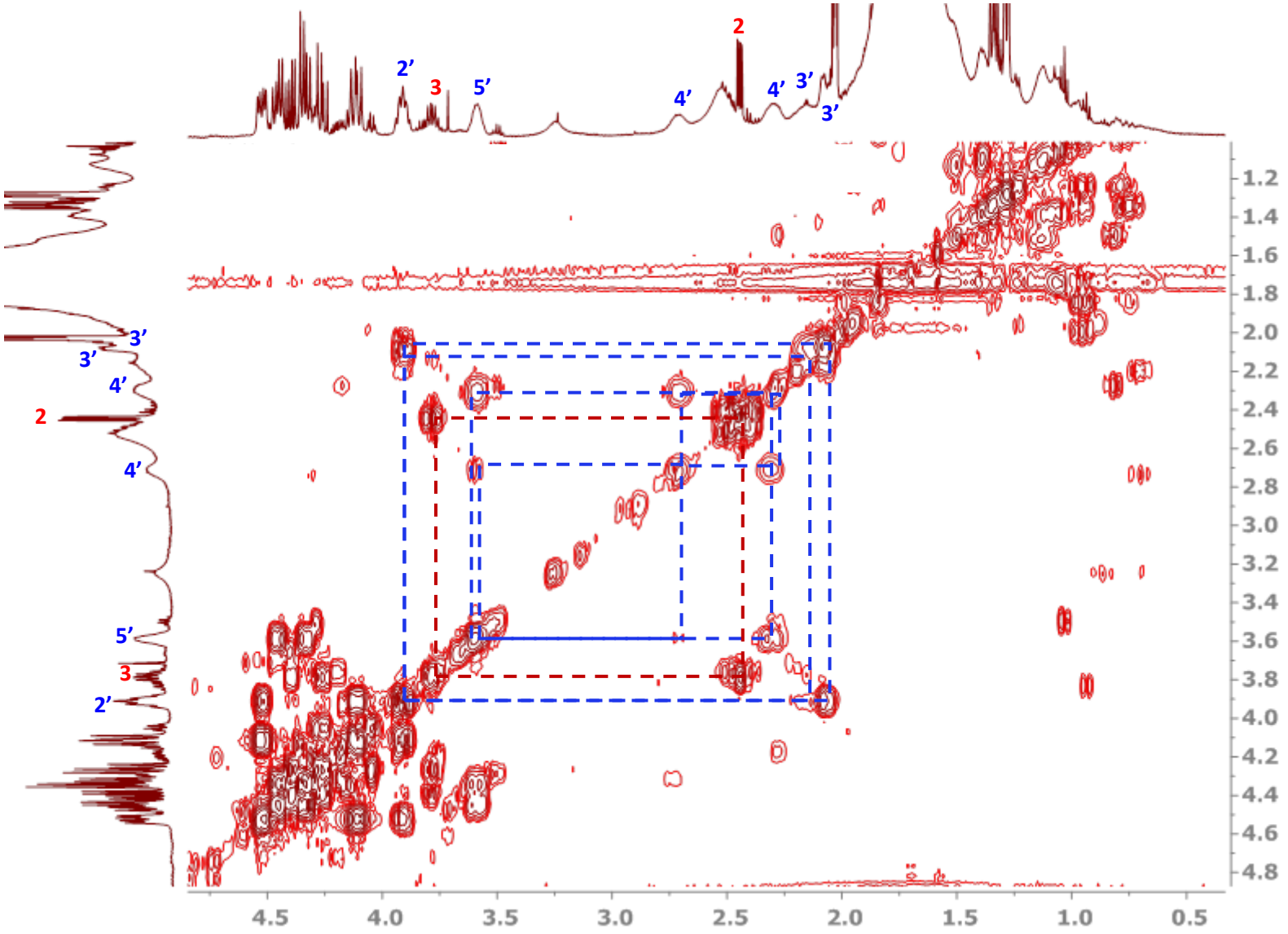


Figure 13. COSY cross peaks on the range 1.5-4.5 ppm

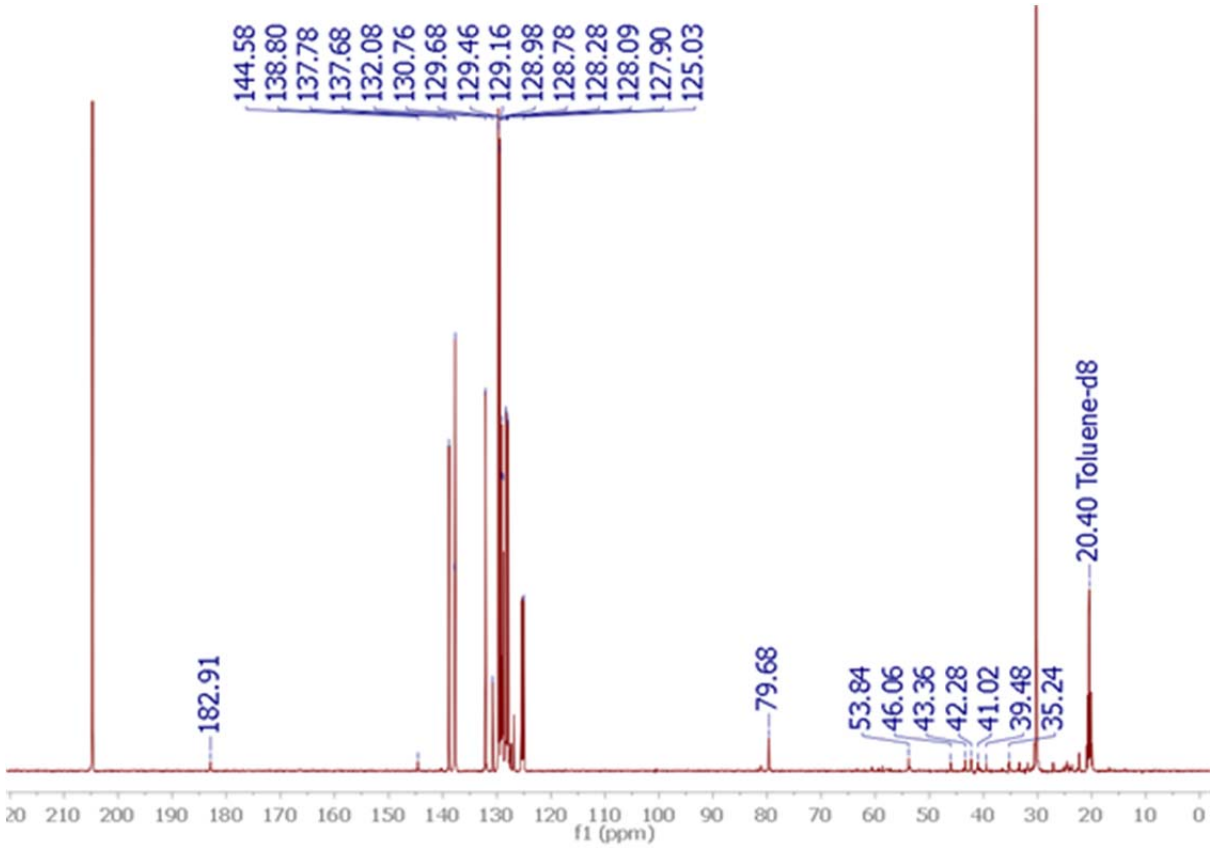


Figure 14. ^{13}C NMR characterization of the catalytic species **{I-3b}** and product **3a**. Performed in the absence of added water and AcOH (Conditions A).

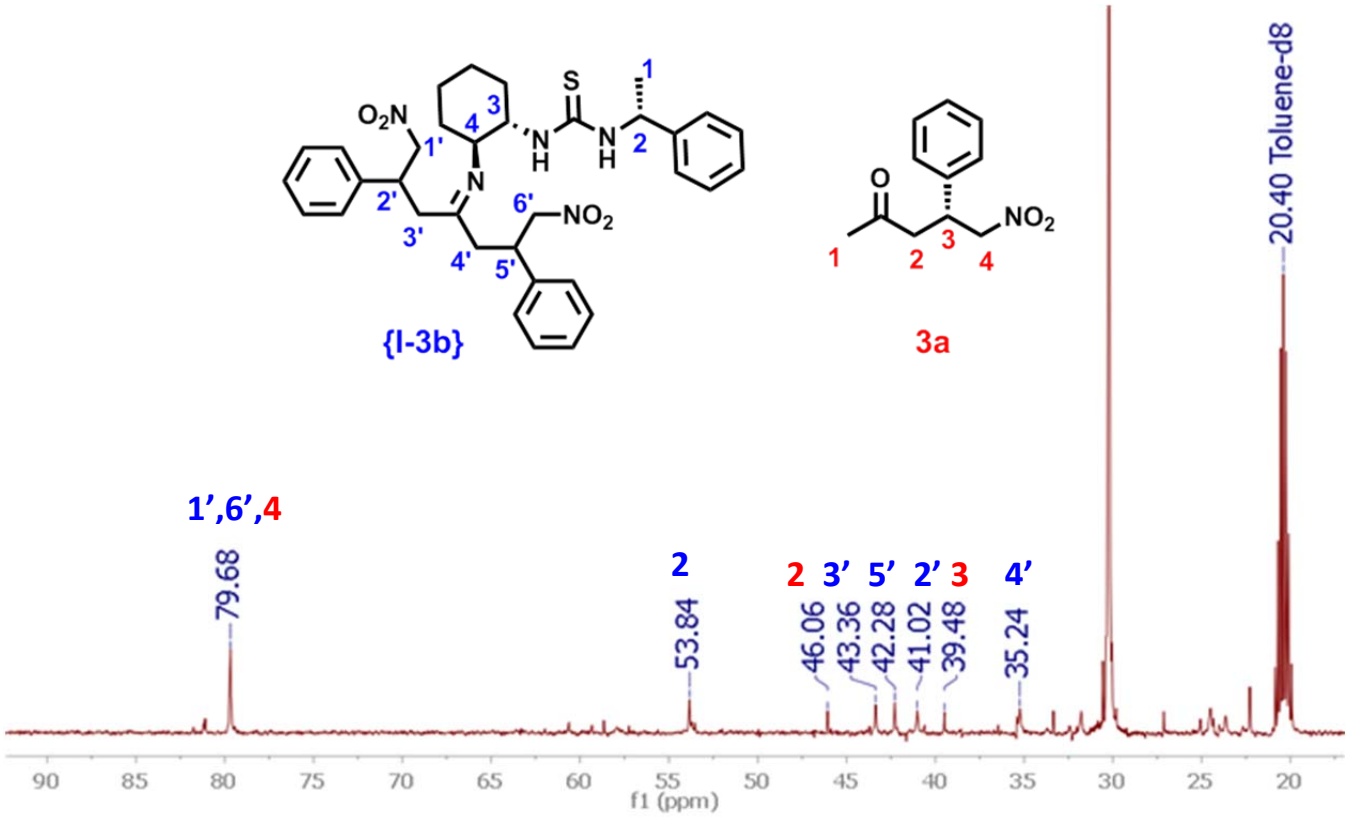


Figure 15. Expansion of ^{13}C NMR spectrum range 20-90 ppm

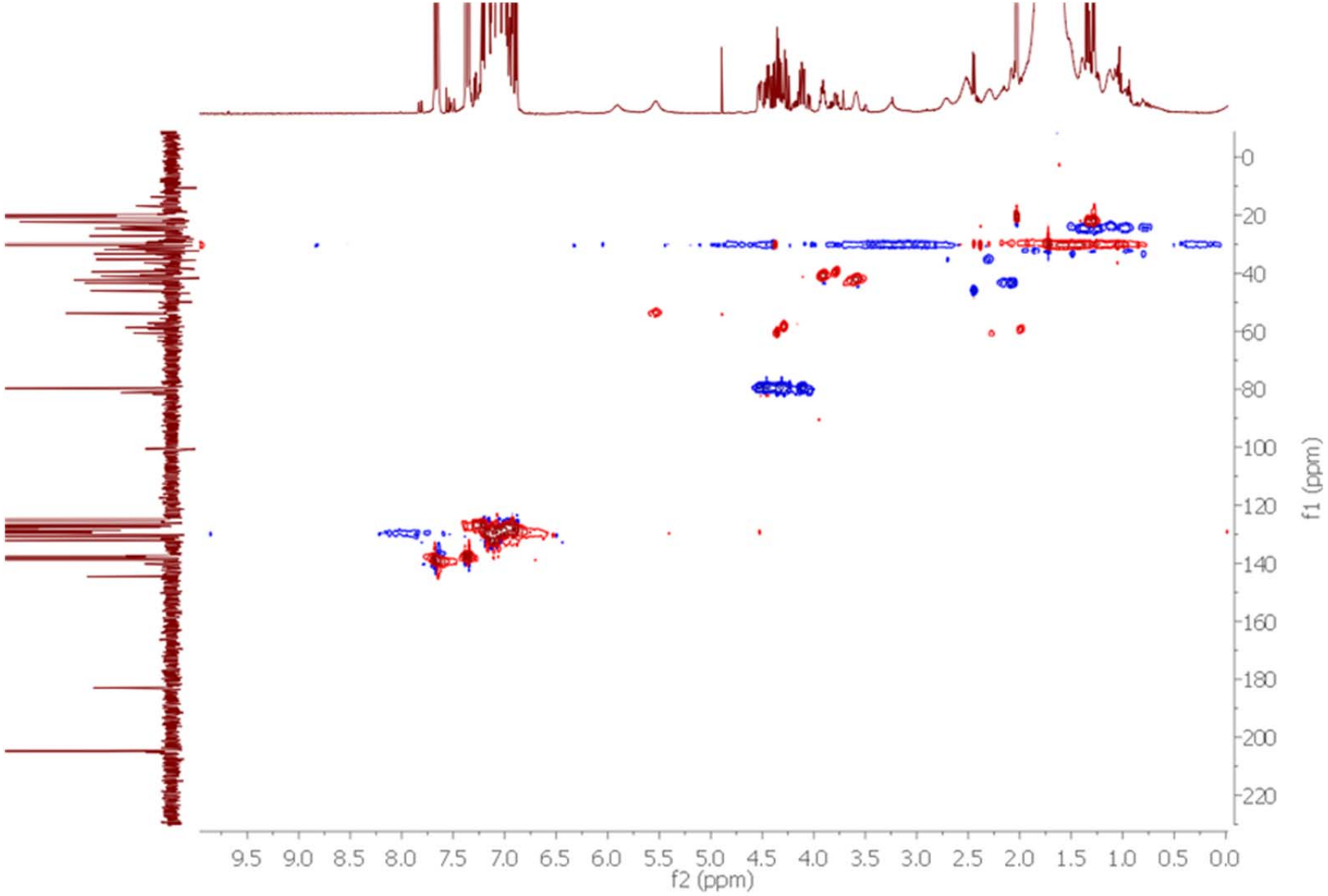


Figure 16. Full HSQC Spectrum in the absence of added water and AcOH (Conditions A).

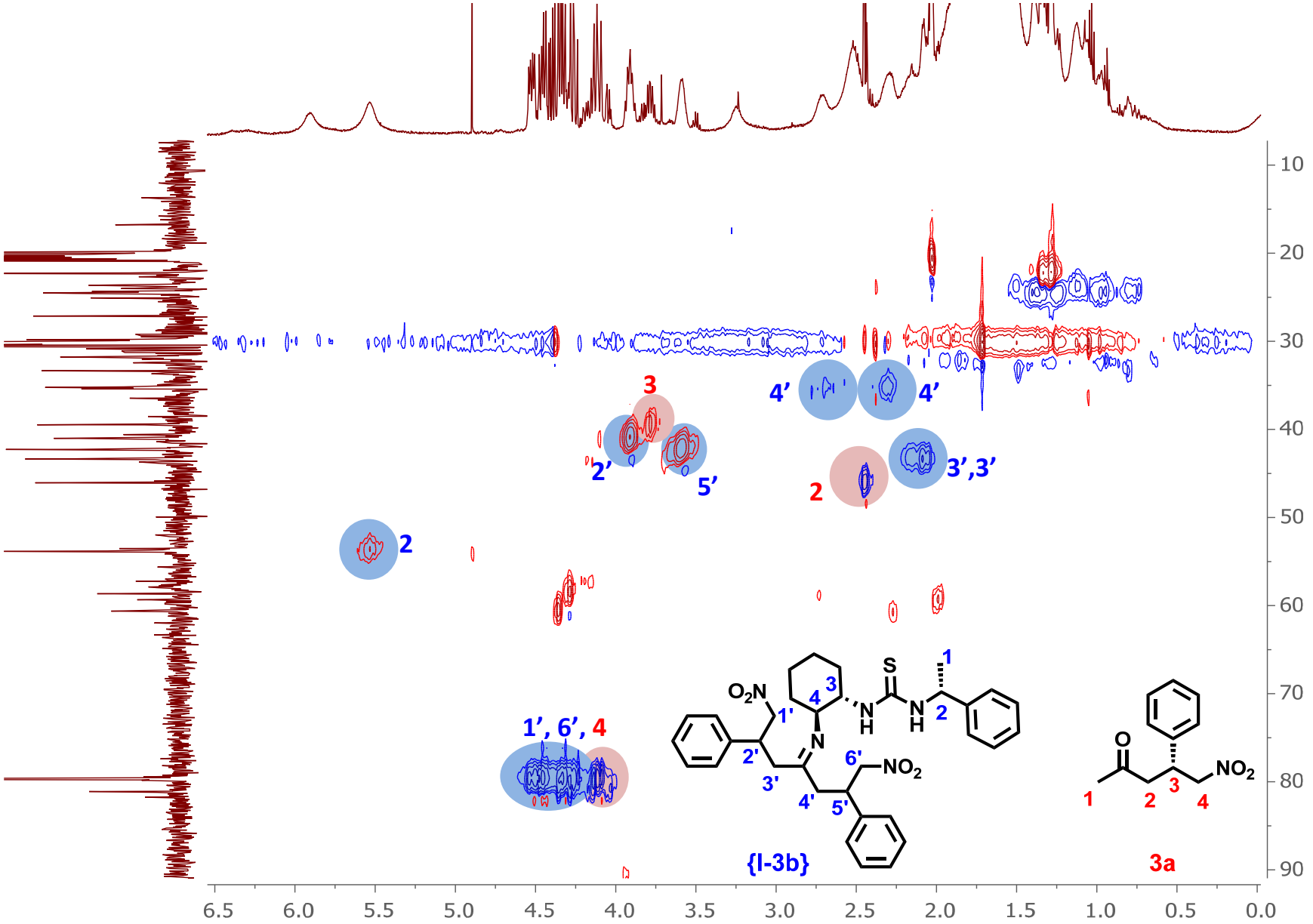


Figure 17. Expansion of HSQC spectrum range 0.0-6.5 ppm

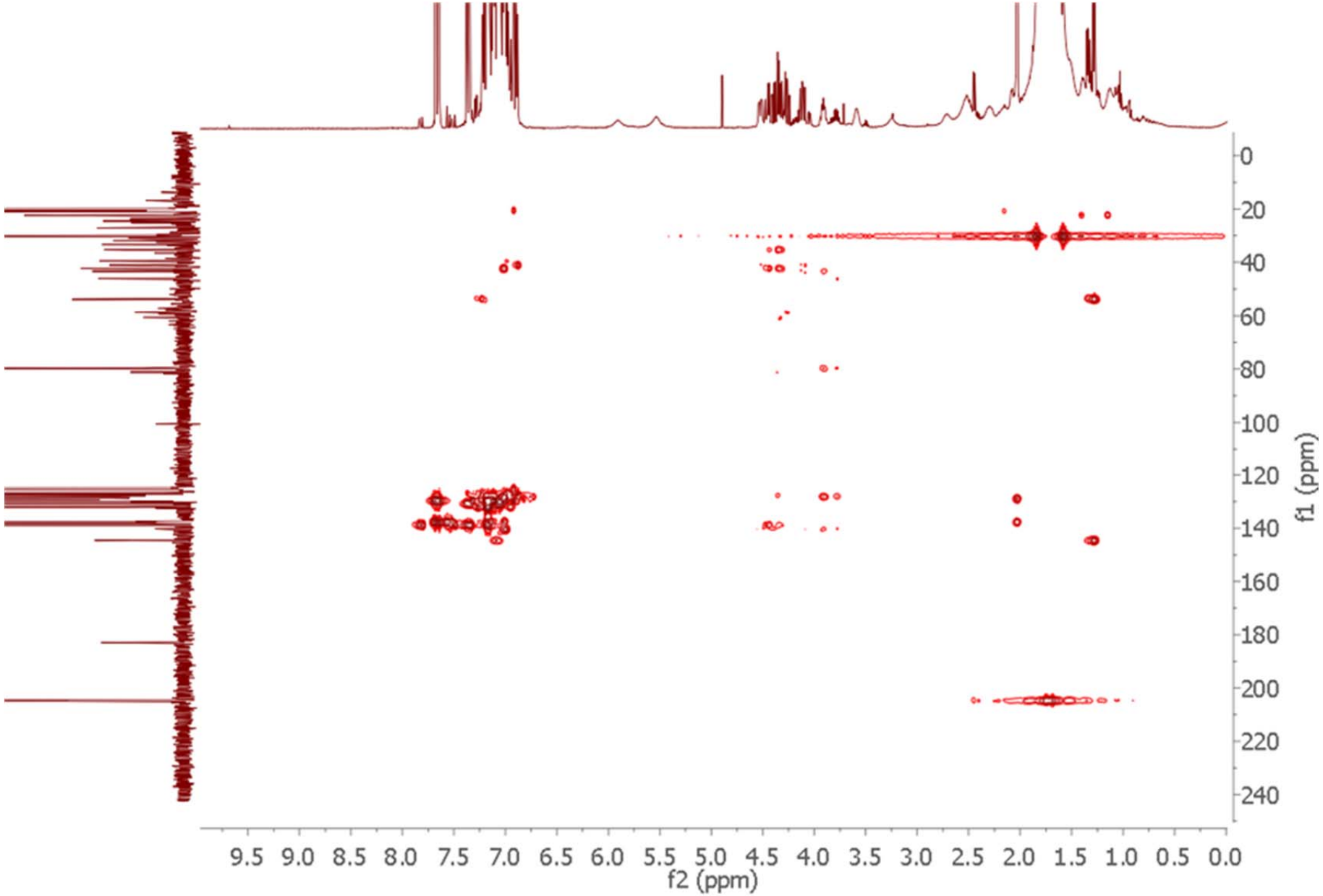


Figure 18. Full HMBC Spectrum in the absence of added water and AcOH (Conditions A).

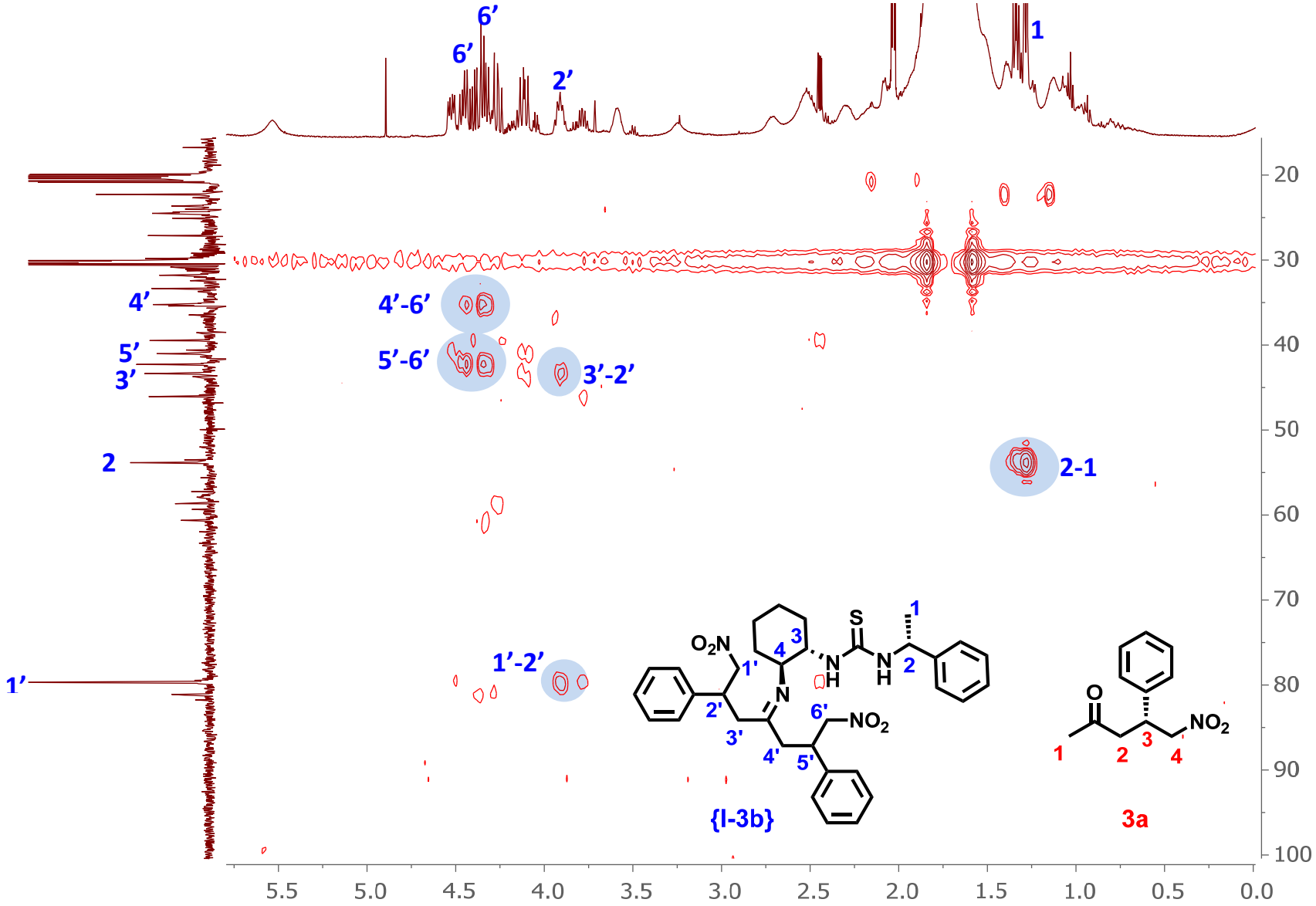


Figure 19. Expansion of HMBC Spectrum range 0.0-5.5 ppm

When the Michael addition was performed in the presence of 10 mol% AcOH and no added water (Conditions B, $[\mathbf{1}]_0$=0.45 M, 10 equiv. acetone, 10 mol% **I,** 10 mol% AcOH), in the beginning of the reaction (up to 30 min), catalyst-product imine intermediate **{I-3a}** could be characterized by NMR.

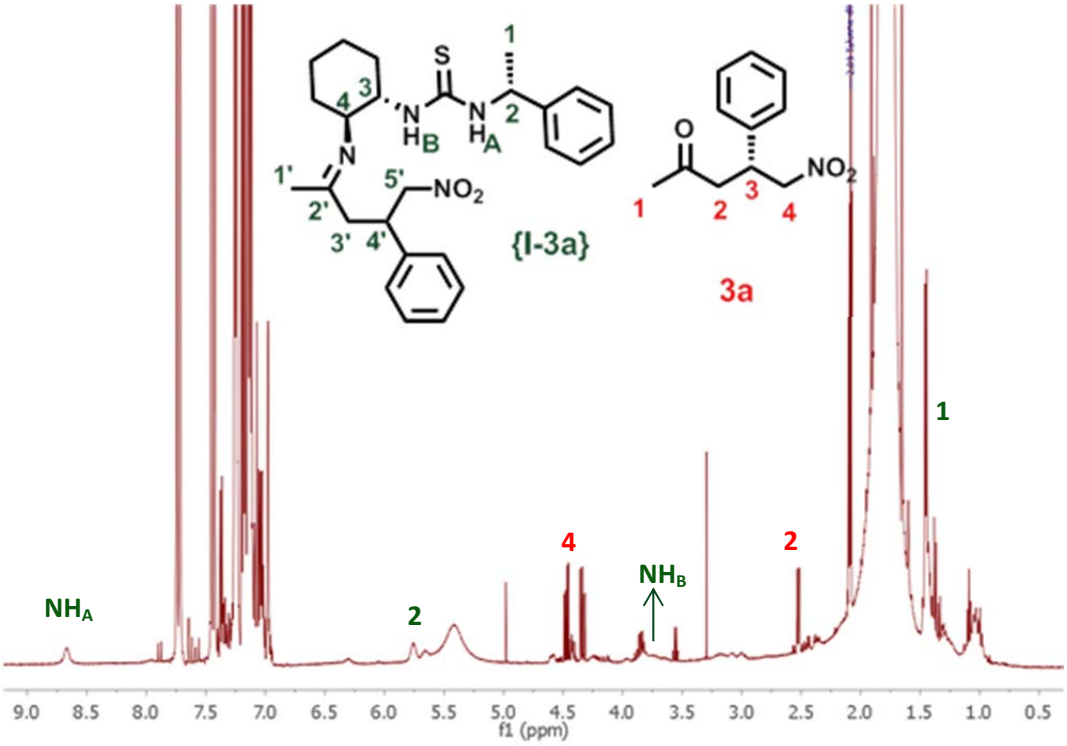


Figure 20. ^{1}H NMR characterization of the catalytic species **{I-3a}** and product **3a** (Conditions B).

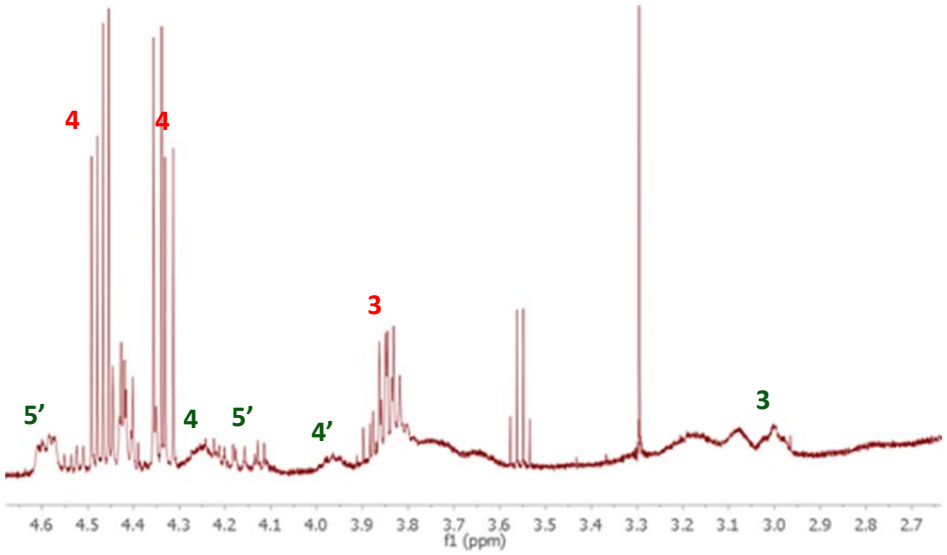


Figure 21. Expansion of ^{1}H NMR spectrum range 2.7-4.6 ppm.

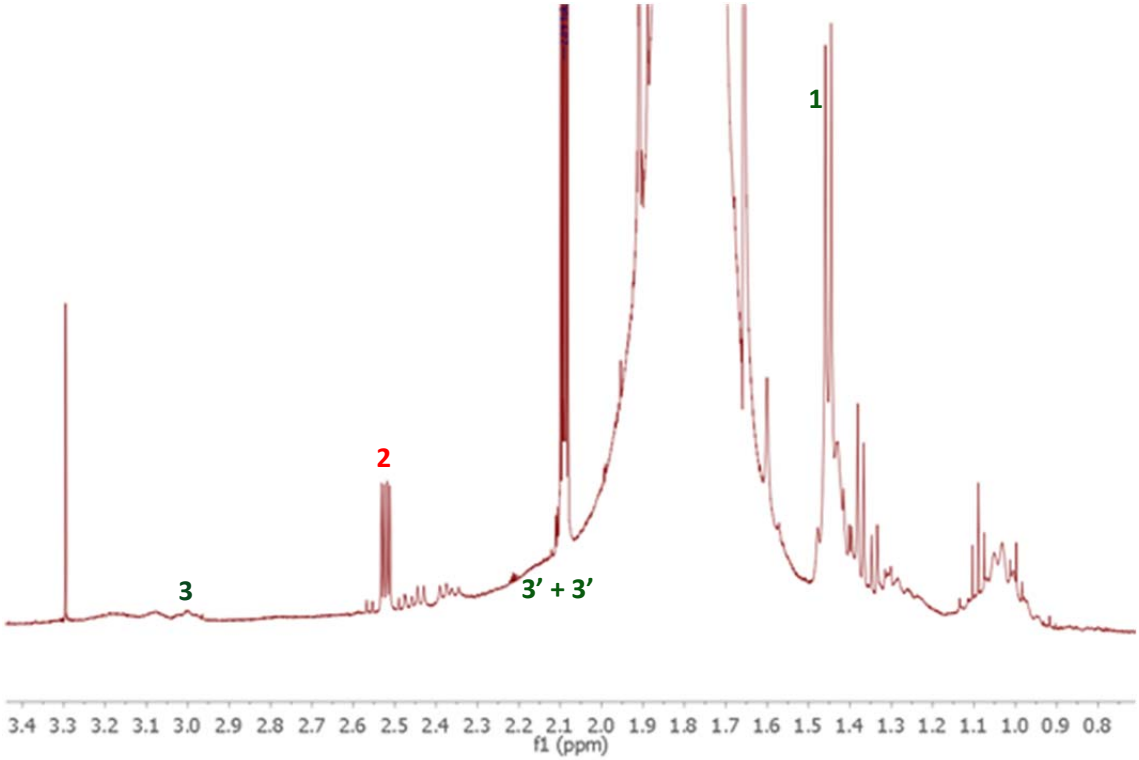


Figure 22. Expansion of ^{1}H NMR spectrum range 1.0-3.5 ppm.

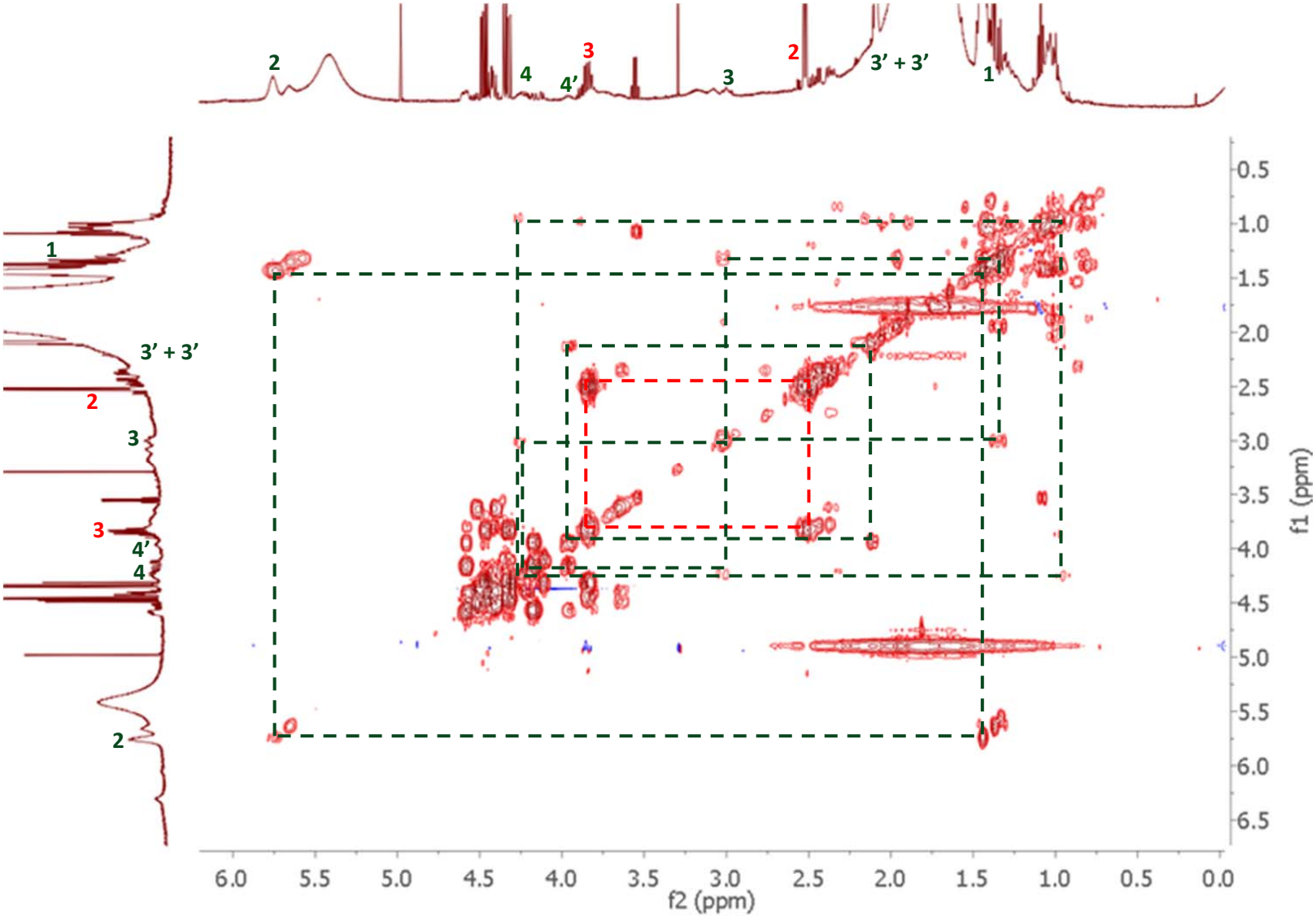


Figure 23. COSY cross peaks on the range 0.5-6.0 ppm

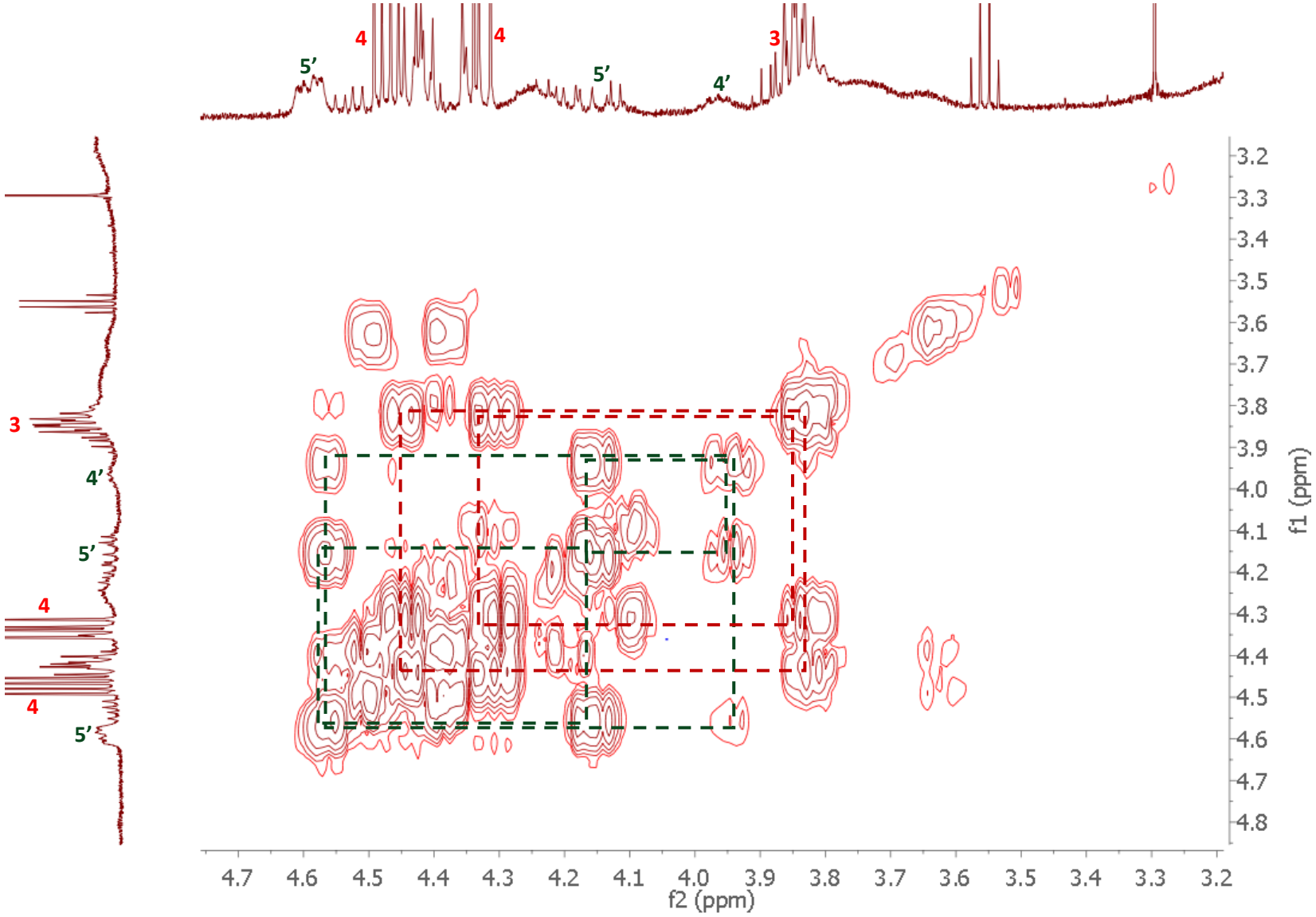


Figure 24. COSY cross peaks on the range 3.5-4.8 ppm

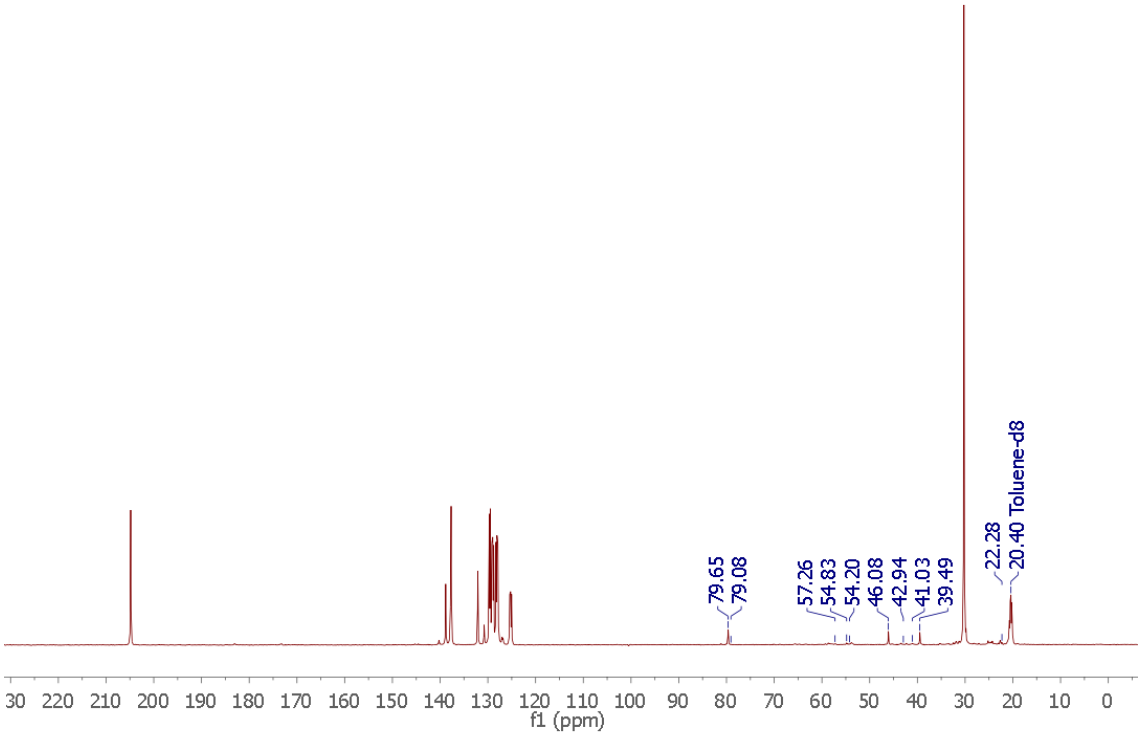


Figure 25. ^{13}C NMR characterization of the catalytic species **{I-3a}** and product **3a** under Conditions B. $[\mathbf{1}]_0$=0.45 M, 10 equiv. acetone, 10 mol% **I**, 10 mol% AcOH.

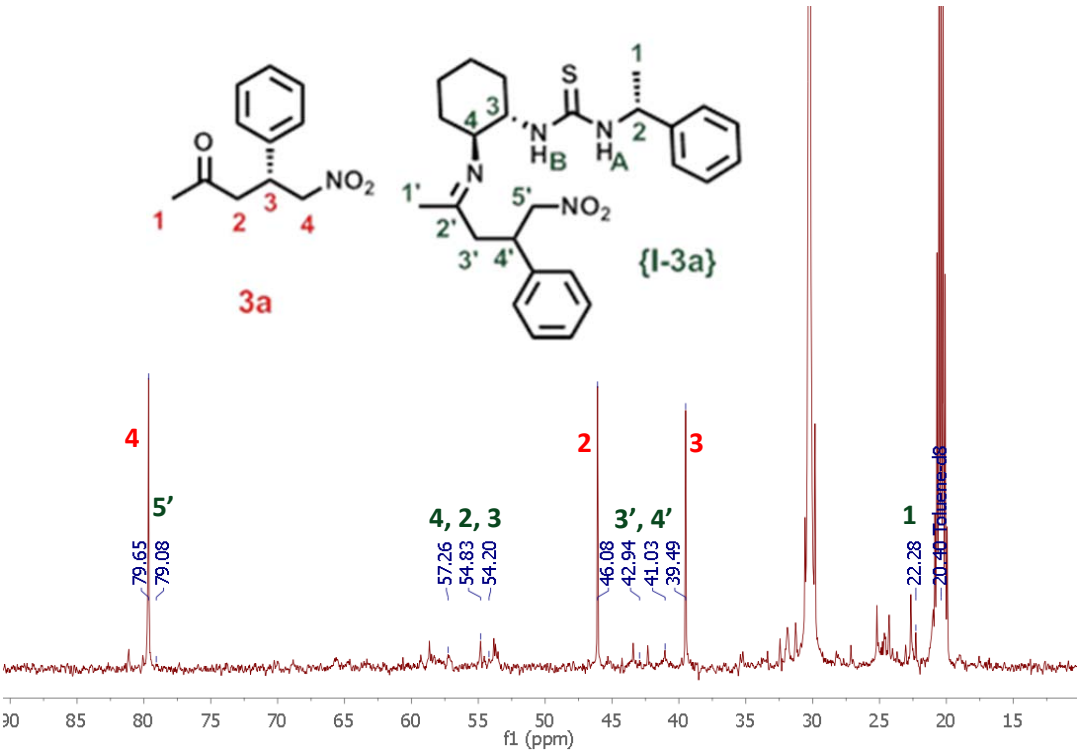


Figure 26. Expansion of ^{13}C NMR spectrum range 20-90 ppm

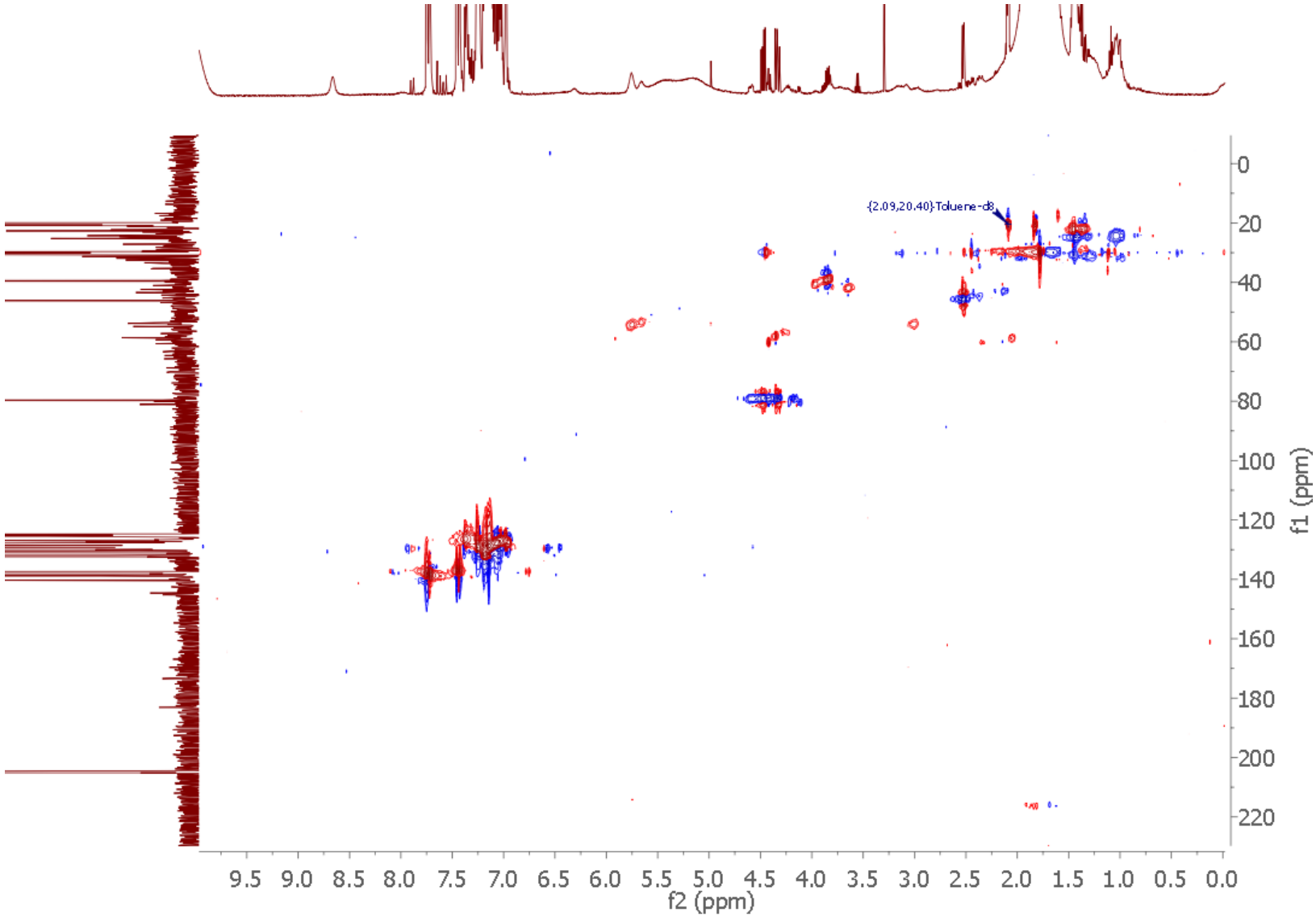


Figure 27. Full HSQC Spectrum under Conditions B. $[\mathbf{1}]_0$=0.45 M, 10 equiv. acetone, 10 mol% **I**, 10 mol% AcOH.

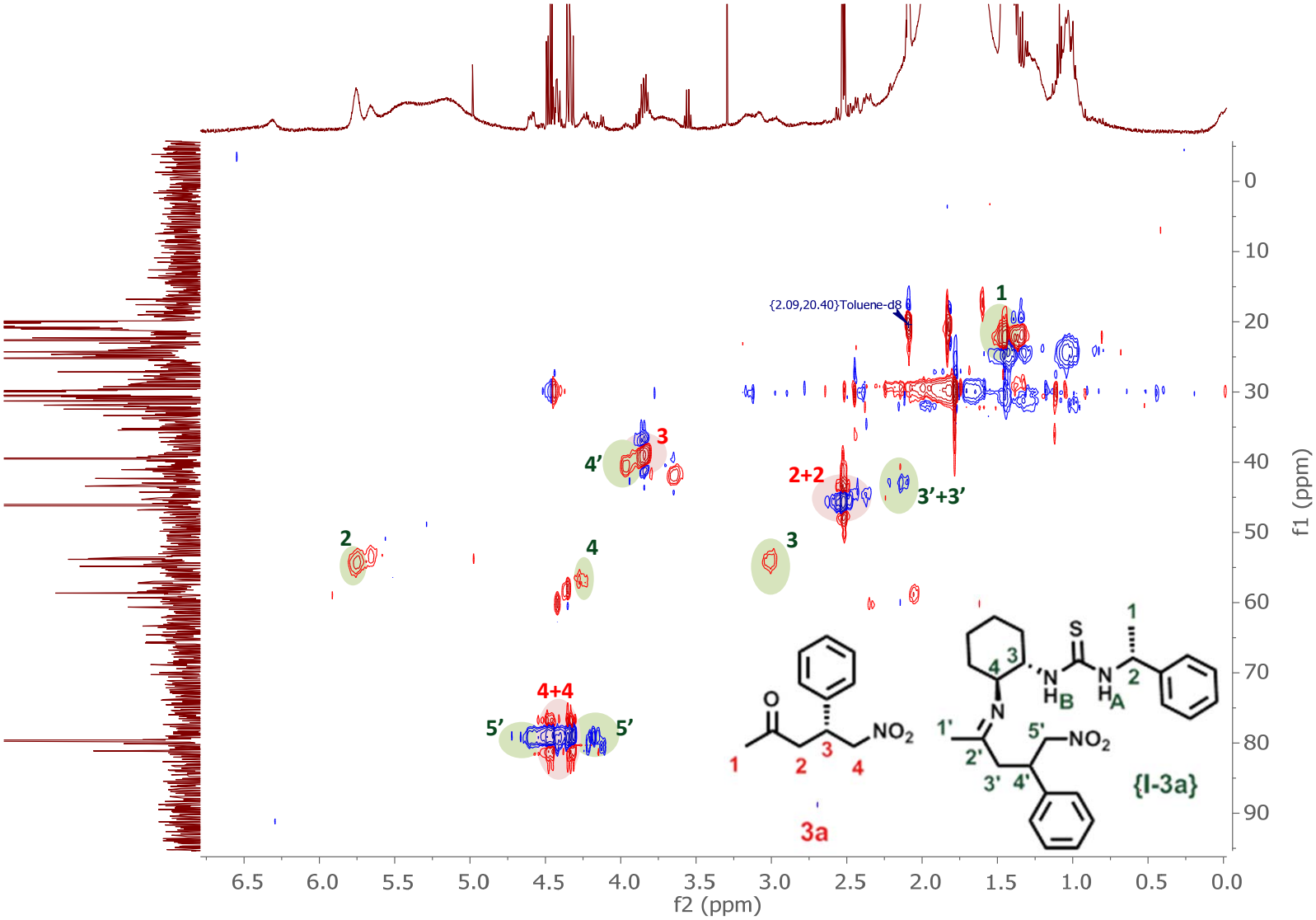
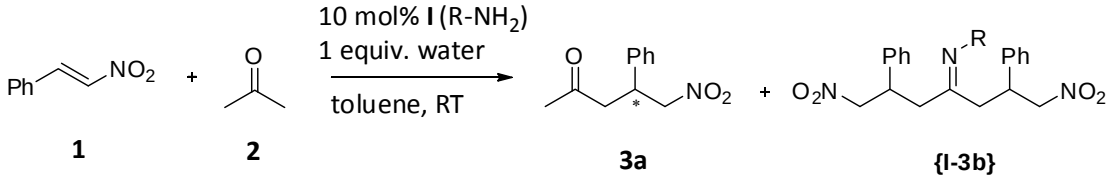


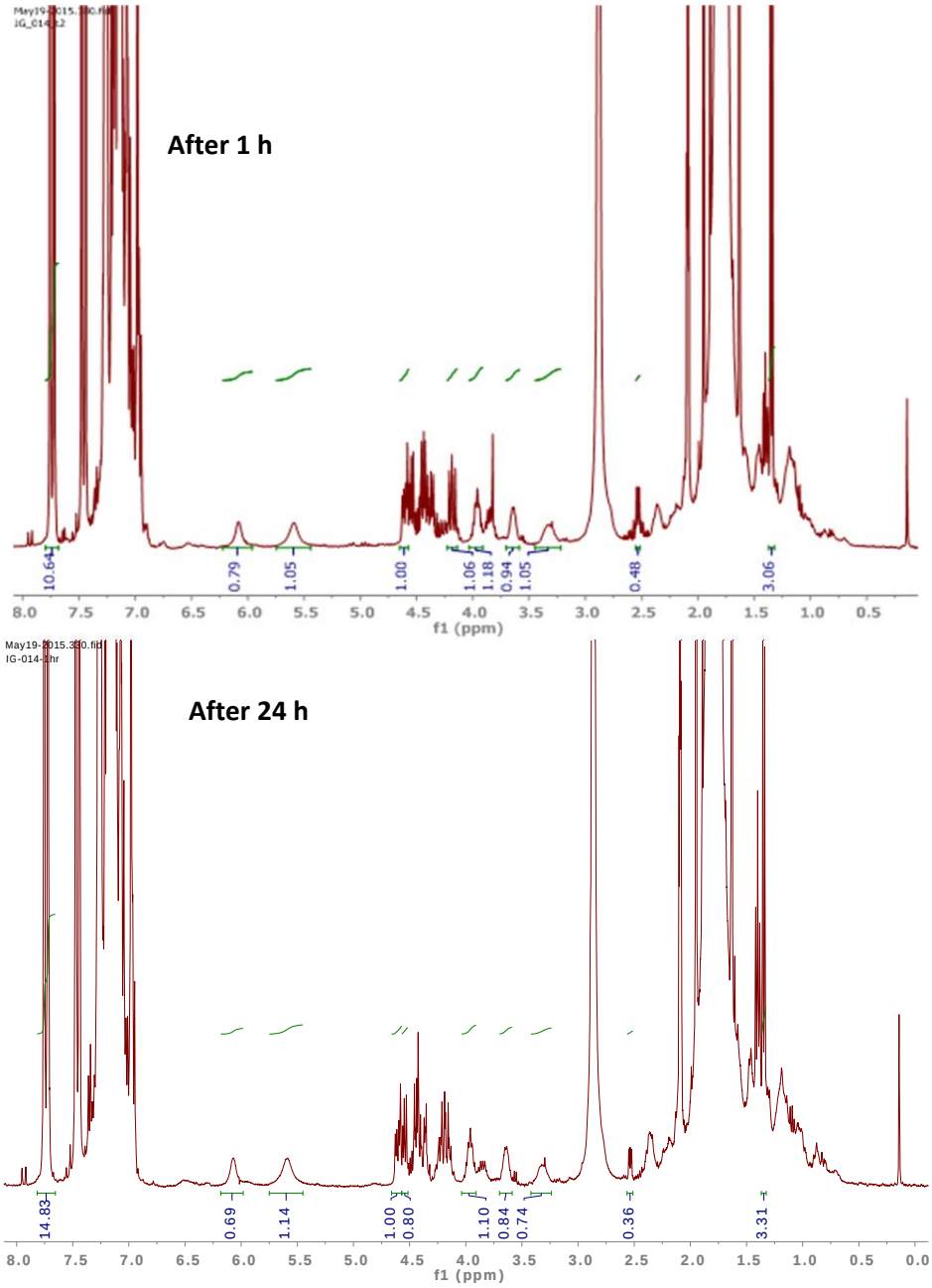
Figure 28. Expansion of HSQC Spectrum range 0.0-6.5 ppm.

4.9. ^{1}H NMR spectra for the reaction run with 1 equivalent of water added but no AcOH

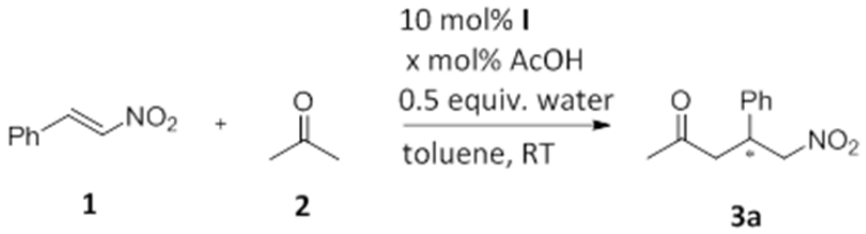


1 **2** **3a** **{I-3b}**

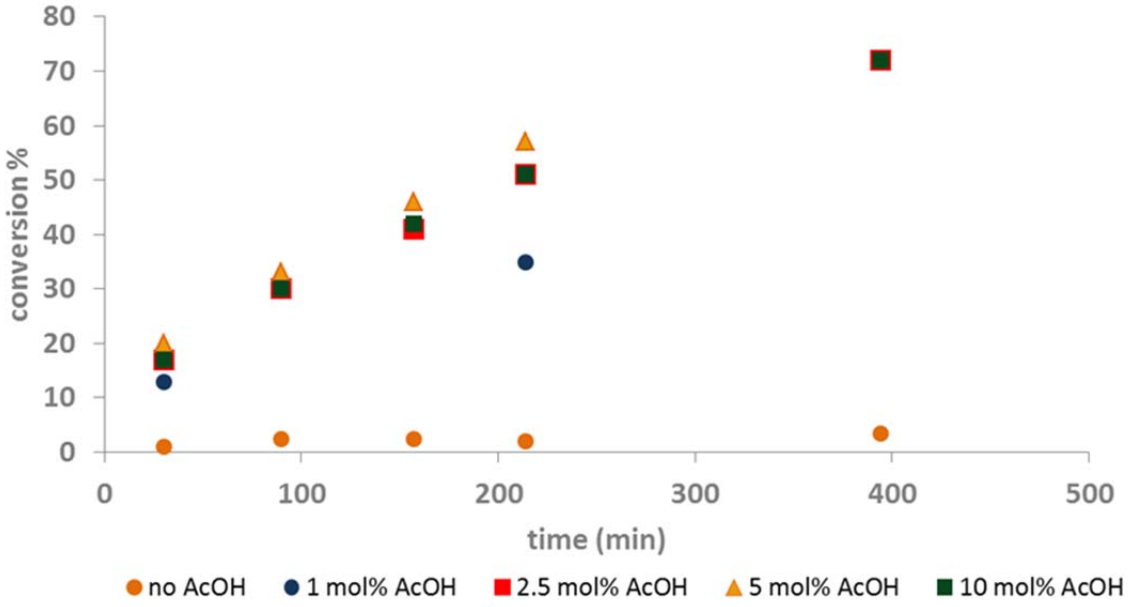
Under acid-free conditions but adding 1 equiv. of water ($[\mathbf{1}]_0$=0.45 M, 10 equiv. acetone, 10 mol% **I**, 1 equiv. water) double addition product imine **{I-3b}** and product **3a** were formed (See Section 7.6). After 24 hours the concentration of the two species remained constant.



4.10. Effect of the amount of AcOH



Effect of AcOH amount in the Michael addition of acetone to nitrostyrene was tested under Conditions C. $[\mathbf{1}]_0$=0.45 M, 10 equiv. acetone, 10 mol% catalyst **I**, x mol% AcOH, 0.5 equiv. water in toluene at rt.



4.11. Dissapearence of nitrostyrene due to the formation of products, intermediates and side-products

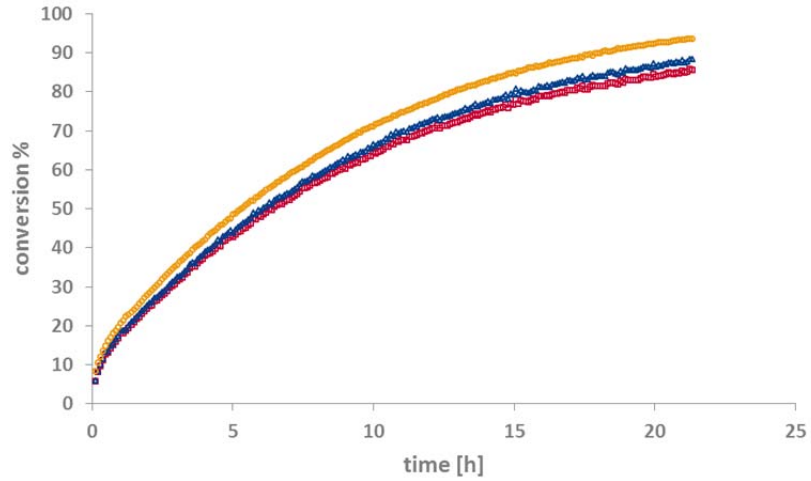


Figure 29. Conversion *vs.* time under ''added water'' conditions (Conditions C). $[\mathbf{1}]_0$= 0.45 M, 10 equiv. acetone, 10 mol% catalyst **I**, 5 mol % AcOH, 1 equiv. water.

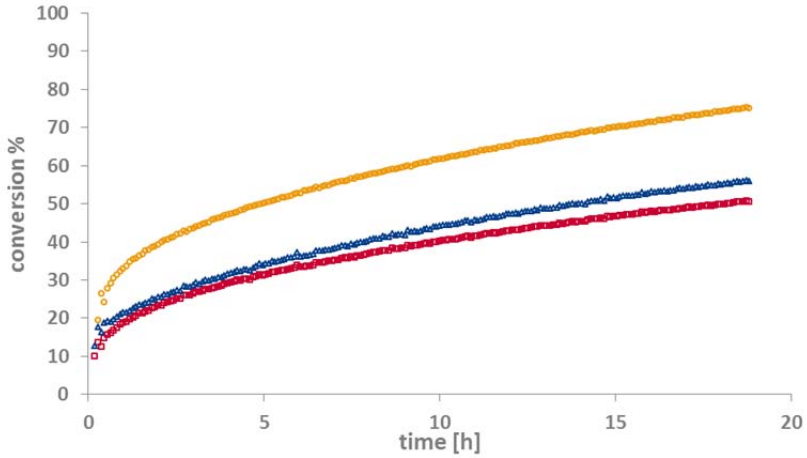


Figure 30. Conversion *vs.* time under ''no extra water added'' conditions (Conditions B). $[\mathbf{1}]_0$= 0.45 M, 10 mol% catalyst **I**, 5 mol % AcOH.

Red squares: conversion calculated based on product **3a** formation

$$conversion\ \% = \frac{[\mathbf{3}\boldsymbol{a}]}{[\mathbf{1}]_0}.\mathbf{100}$$

blue triangles: conversion based on product **3a** plus double-addition side product **3b** formation

$$conversion\ \% = \frac{[\mathbf{3}\boldsymbol{a}] + [\mathbf{3}\boldsymbol{b}]}{[\mathbf{1}]_0}.\mathbf{100}$$

yellow circles: conversion based on nitrostyrene disappearance

$$conversion\ \% = \frac{[\mathbf{1}]_0 - [\mathbf{1}]\boldsymbol{t}}{[\mathbf{1}]_0}.\mathbf{100}$$

4.12. Proof of the ''free catalyst'' does not deactivate

The reactions were carried out under three different sets of reaction conditions (Conditions A-C). For all three sets of reactions, $[\mathbf{1}]_0$= 0.45 M, 10 equiv. acetone and 10 mol% catalyst **I** were used. First, the catalyst (7.5 mg, 0.027 mmol) was weighed directly into the NMR tube, and then the reagents were added from common stock solutions in the indicated order. The catalyst was exposed to nitrostyrene for 3 hours prior to acetone addition. The reaction was then recorded continuously by NMR.

- **Stock solution A (nitrostyrene):** 201.4 mg (1.35 mmol) nitrostyrene in 1 mL d_8-toluene
- **Stock solution B (AcOH):** 81.2 mg (77.4 µL, 1.35mmol) of acetic acid in 1 mL d_8-toluene. 0.1 mL of this solution was diluted to 1 mL d_8-toluene.

  Final solution: 0.135 mmolAcOH / mL solution

Conditions A, in the absence of added water and AcOH:

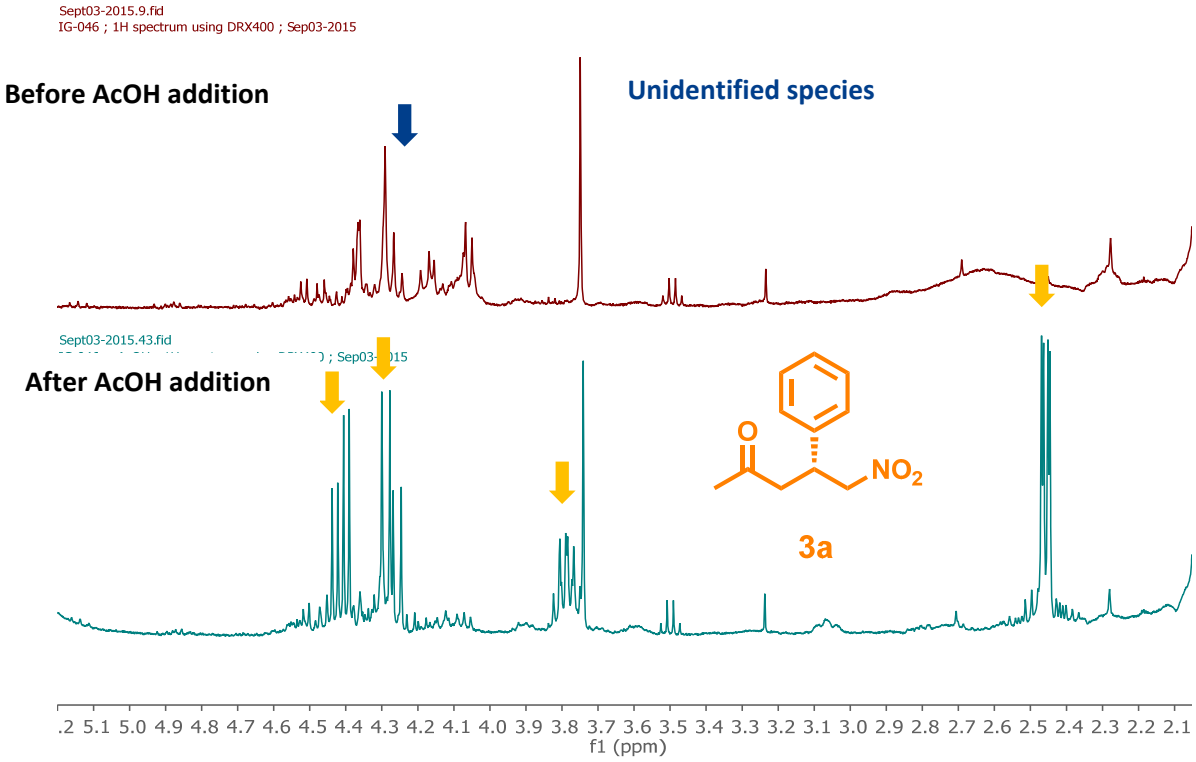
+ 200 µL d_8-toluene
+ 200 µL stock soln. A

Wait 3 hours

+ 200 µL acetone

Wait 1 hour

+ 100 mL stock soln. B



Conditions B, with 5 mol% AcOH and no extra water added:

+100 µL toluene-d_8

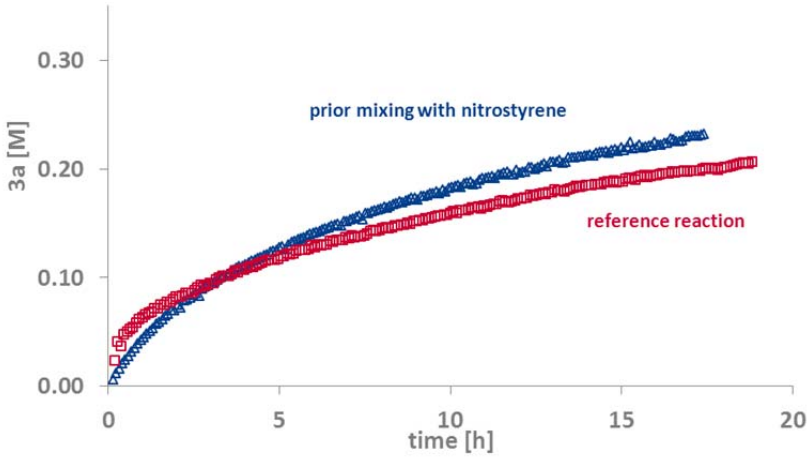
+ 100 µL stock soln. B

+ 200 µL Stock soln. A

Wait 3 hours

+ 200 µL acetone

Formation of product **3a** was observed similarly to a reference reaction without catalyst pre-mixing with NS.



Conditions C, with 5mol% AcOH and water added (1 equiv.):

+100 µL d_8-toluene

+ 100 µL Stock soln B

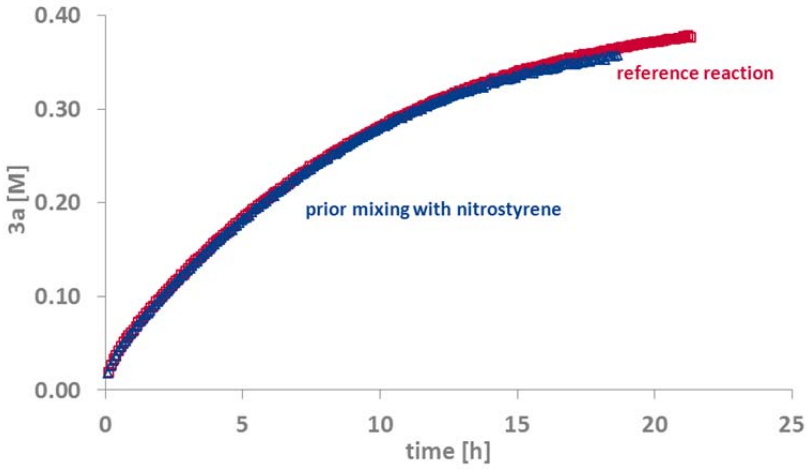
+ 200 µL Stock soln A

+ 4.86 µL H_2O

Wait 3 hours

+ 200 µL acetone

Formation of product **3a** was observed identical to a reference reaction without catalyst pre-mixing with nitrostyrene.



4.13. Proof of no product inhibition

An initial kinetic experiment by ^{1}H NMR (red squares) was repeated under identical conditions (Conditions B, $[\mathbf{1}]_0$=0.45 M, 10 equiv. acetone, 10 mol% catalyst **I** and 5 mol% AcOH) and recorded continuously by NMR. The amount of product formed during the first 2.5 hours (yellow circles) was calculated as 0.114 M (15 mg, 0.0684 mmol). Another experiment was carried out under identical conditions adding the calculated amount of product at the beginning of the reaction. The overlay of these two traces (product added experiment and the reference experiment) concludes there is *no product inhibition* responsible for this reaction.

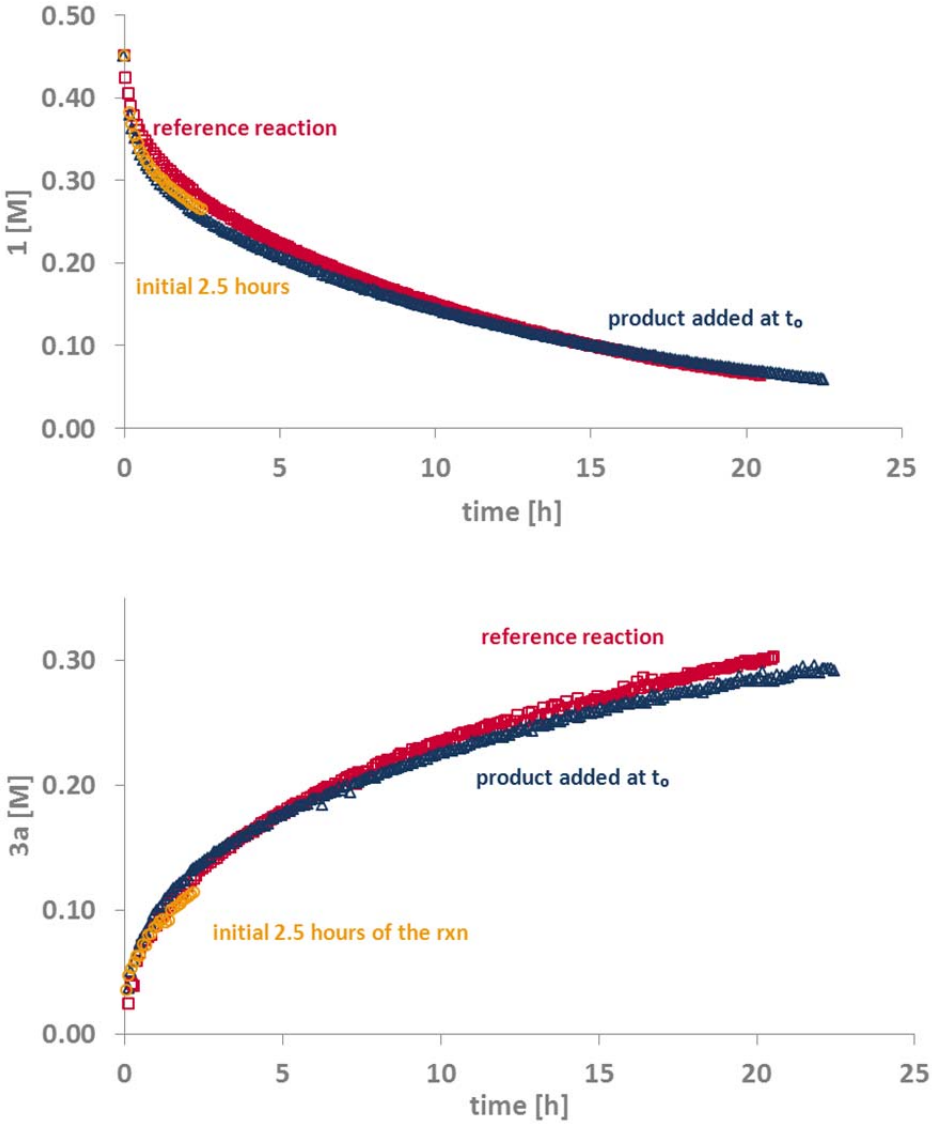


Figure 31. Proof of no product inhibition by carrying out reaction with and without addition of product at t_0.